University of Southern Queensland

EVALUATING THE SPATIAL DISTRIBUTION OF ENDANGERED FROGS IN NORTHERN QUEENSLAND AND THE THREATS TO THEIR CONTINUED SURVIVAL

A Thesis Submitted

By

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ABSTRACT

The conservation of threatened species is hampered in the absence of fundamental ecological information, such as species' abundance and distribution. The aim of this study is to determine the spatial distribution of four species of critically endangered frogs in order to clarify their conservation status and determine potential threats to their distribution. These species are: *Litoria lorica, Litoria nyakalensis, Taudactylus acutirostris* and *Taudactylus rheophilus*. These frogs have large knowledge gaps relating to their preferred habitat, factors that affect distribution, current distribution and threats, undermining effective conservation strategies. This study used both climatic and environmental variables, combined with the historical, verified sightings of these frogs to determine potential, suitable habitat. The variables used include land use, land cover, precipitation, temperature variables, elevation and distance to water sources. These were pre-processed using ArcGIS and run through MaxEnt to generate species distribution models. The distribution models were mapped using ArcGIS and the suitability of this habitat was shown as "not suitable", "low suitability", "moderate suitability" and "high suitability" with a tabulation of the hectares and variables that influence this distribution. These models show that there are significant areas of high suitability habitat remaining for each species with 164,302 hectares (9.2% of the total area) for *Litoria lorica*, 93,179 hectares (5.2%) for *Litoria nyakalensis*, 82,840 hectares (4.7%) for *Taudactylus acutirostris* and 252,481 (14.2%) hectares for *Taudactylus rheophilus*. The data was validated using the Area Under the ROC (Receiver Operating Characteristics) Curve (AUC). The average AUC was 0.76 giving a high degree of confidence in the accuracy of the model outputs. The future climate models show that by 2040 the amount of habitat that is suitable, specifically highly suitable, will have decreased to 128,641 hectares for *Litoria lorica* (2%) in 2040, 91,787 hectares for *Litoria nyakalensis* (0.1%), 81,492 for *Taudactylus acutirostris* (0.1%) and increased to 304,153 (2.9%) hectares for *Taudactylus rheophilus*. This is possibly due to the climatic conditions changing to suit the optimal conditions for *Taudactylus rheophilus*. In 2080, this trend continues to the point where there is very little suitable habitat within the Wet Tropics for any of these species and therefore it is obvious that significant measures need to be implemented in order to mitigate the effects of climate change to save these species.

CERTIFICATION OF THESIS

I, Emily Larsen, declare this Masters thesis titled '*Evaluating the spatial distribution of endangered frogs in Northern Queensland and the threats to their continued survival*', is my own work and there are no conflicts of interest in this study. This thesis is not more than 100,000 words exclusive of tables, figures, appendices, bibliographies, references and footnotes. This thesis contains no material that has been previously submitted, in whole or part, for the award of any other academic degree or diploma. Except where otherwise indicated, this thesis is my own work.

1/12/22

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

ALA –	Atlas of Living Australia
AUC -	Area Under the Curve
Bd –	*Batracochytrium dedrobatidis*
FNQ –	Far North Queensland
GIS –	Geographic Information Systems
GBIF	Global Biodiversity Information Forum
GPS –	Global Positioning System
IUCN -	International Union for the Conservation of Nature
MaxEnt –	Maximum Entropy modelling software
PA –	Protected Area
SDM –	Species Distribution Modelling
WHA -	World Heritage Area

CHAPTER 1: INTRODUCTION

1.1 Background

The Wet Tropics is a World Heritage listed area which represents a major stage in the evolutionary history of Earth (Richards 2002; Alford & Rowley 2007; Pearson 2018). It contains a wide variety of extant species of both flora and fauna that are relics or descendants of species that were found in the area 60 million years ago (Stork & Turton 2009; Puschendorf et al. 2013). Many of the animals found here are direct descendants of those that lived in the area during Gondwanan times (WTMA 2016). This area is floristically and structurally the most diverse region in Australia (Puschendorf et al. 2013; DWAE 2021) and this high level of diversity and endemism is the reason that the Wet Tropics is considered a crater of life (WTMA 2016).

Primitive marsupials have been documented to have evolved in the Wet Tropics 40 million years ago and the most primitive, still extant species of marsupial, the Musky Rat-Kangaroo, is now only found here (Stork & Turton 2009). It is also the only place on Earth with a mixing of Australo-Papuan songbird lineages, a relic from 15 million years ago when the Australian and Papuan land masses were much closer together (WTMA 2016). Ancient plants are also well represented here with high levels of endemism. This is due to the stable climate of the Wet Tropics, allowing ancient plants and animals to thrive as the climate changes beyond their limits elsewhere (BOM & CSIRO 2019).

This stable climate allows for the continuation of these species while boasting amazing scenery (Alford & Rowley 2007; Pearson 2018). Ancient mountains house large waterfalls while deep gorges interweave spectacular river systems (Alford & Rowley 2007; Pearson 2018; DWAE 2021). It is a megadiverse region characterised by high levels of rainfall, particularly in the wet season, creating a unique expanse of rainforest (WTMA 2016). The Wet Tropics Management Authority (WTMA) also has a listing of Very Important Protected Species (VIPS) to which half the plants and animals in the Wet Tropics qualify. These species are recognised as having high conservation significance through at least one out of four criteria. To qualify a species must be: locally endemic, ancient or evolutionarily distinct and/or classed as ecologically rare or threatened through the International Union for the Conservation of Nature (IUCN) (WTMA 2016; DES 2021).

1.2 Statement of the Problem

Australia has a terrible record in terms of species extinctions. Over the past 200 years more species have gone extinct in Australia than anywhere else in the world (Reside et al. 2019a), making Australia a global epicentre of extinctions. More than 50% of Australia's frog species are listed as threatened or higher by the IUCN. Of this 50%, 17% frog species are critically endangered due to significant declines in the 1980's and 1990's (Hero & Morrison 2015). This is the highest listing by any country in the world and requires significant intervention. Reversing the decline of native frog species has been called one of the greatest challenges in global conservation (Clarke 2006).

Only now are we starting to understand what generations have taken for granted and exploited. Despite frogs being an integral part of any environment, as part of the food chain and a regulator of both the food chain and the environment (Kriger 2017), there is little work that has been done on Australian frogs and only a handful have been fully studied (Murray et al. 2011). Most frogs in Australia are understudied, underappreciated and exceedingly overlooked. There are several whose distribution has never been understood and few who are only known by one or two specimens (Clulow & Swan 2018). Frog species are even still being discovered in Australia, including the Sunset Frog in the south west of Western Australia in 1997 (Clulow & Swan 2018) and seven species in Queensland since 2007, six of which are restricted to the Wet Tropics (Alford & Rowley 2007). The damage we currently face is great but there is still a chance of recovery for many species.

As many of the species of the Wet Tropics, including the frogs, are direct descendants or genetically very similar, to those that were around thousands of years ago they are evolved to thrive in a world that no longer exists (WTMA 2015). Therefore, these species will have a harder time adapting to changes in the climate and are more likely to have a narrow geographic range and be considered rare. This will mean that these species are more susceptible to extinction processes, with any species trying to adapt attempting to do so in an environment that is no longer amorous to dispersal or migration.

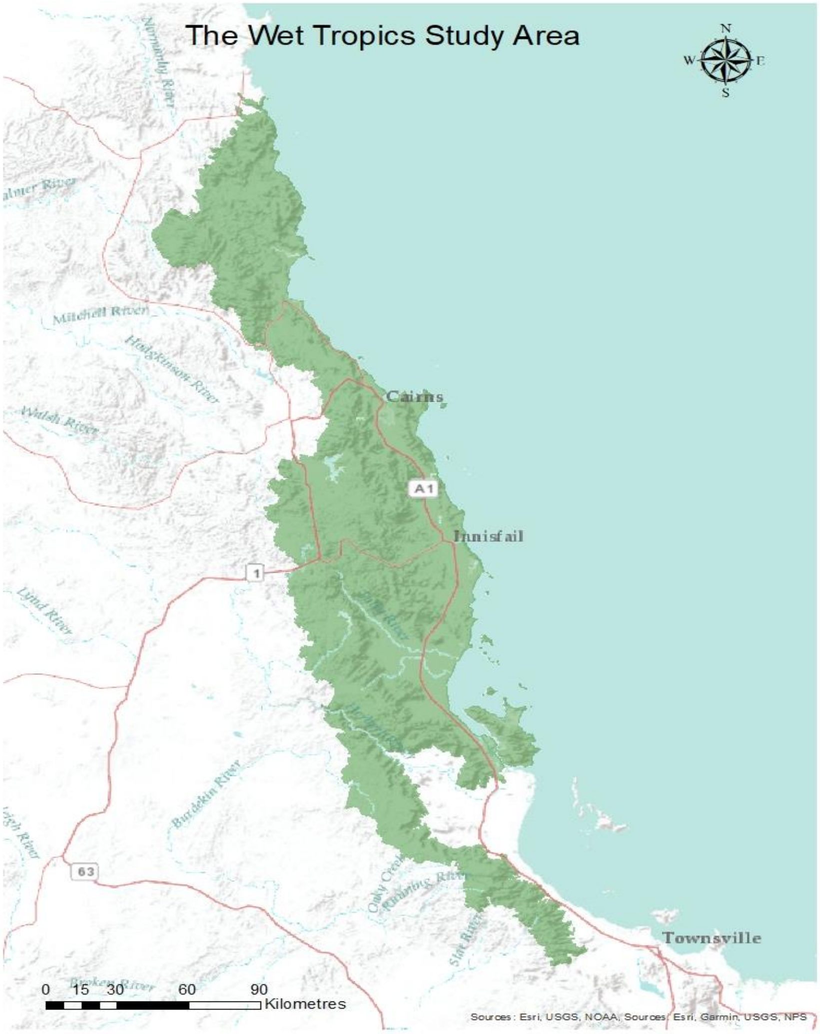

Figure 1: The boundaries of the Wet Tropics

New technologies are constantly being invented that can provide a new paths for determining species distributions, densities and habits (Cresswell & Murphy 2016). Technology such as species distribution modelling (SDM) which combines historical data with climatic and environmental variables to estimate the environmental niche and subsequently the environmental suitability (Puschendorf et al. 2013). This then determines areas of suitable habitat within a defined area. Species distribution models do not appear to have been done for the species used in this study in the past and information on these species is woefully lacking. The environment of the Wet Tropics has also prevented thorough searches using traditional methods due to harsh terrain and steep mountainsides interspersed by waterfalls and other natural barriers (Pearson 2018). Much of the Wet Tropics remains understudied, the western side, in particular. The river system has also not been fully mapped (Pearson 2018), leading to potential areas of rediscovery or discovery of frog species. The current spatial range of these species is currently unknown and it is not clear how this distribution will be affected by climate change. It is also not clear how these frogs are affected by other threats, or even what these other threats are.

1.3 Significance of the Study

There are four critically endangered frogs endemic to the Wet Tropics with little data known about each of them. They (*Litoria lorica, Litoria nyakalensis, Taudactylus acutirostris* and *Taudactylus rheophilus)* were documented to have dramatically declining populations in the 1980's and 1990's although the proximate cause remains elusive. When researchers failed to find remnants of known populations the frogs were declared extinct. This changed in 2008 with the rediscovery of a population of *Litoria lorica*, found outside its known range and lower in elevation than it was thought to inhabit (Hoskin & Puschendorf 2014). It is now currently stable in very low numbers and in two separate populations. This provides hope for the three other species of frog in this study who still have not been officially recorded in over two decades despite efforts by researchers. Most of the rediscoveries of thought to be extinct species that have occurred worldwide have been in areas that were considered marginal or unsuitable habitat (Puschendorf et al. 2013).

This study investigates the possibility of these species still being in existence in previously unidentified parts of its distribution and identifies areas of suitable habitat for each species within the Wet Tropics. Data related to these species has been slow to emerge and the signs of the declining populations were not acknowledged for decades. Little work has been done on *Taudactylus acutirostris* or *Taudactylus rheophilus* since their discovery in the early 1900's and there continues to be significant research gaps.

This study aims to address these issues and research gaps in order to aid management actions. As conservation strategies are developed to target a specific species or group of species, knowledge of the ecology of that species or group has to be available in order for the conservation strategies to be considered effective. This is why populations of these species need to be found and studied in order to gather baseline data and create these conservation strategies. As Puschendorf et al. (2013) state, predicting species declines and shifts are essential for the implementation of effective conservation strategies and directing future research for that species. As very little is currently known about the current distribution, more investigating needs to be completed before the conservation status of these species can be verified or updated (IUCN 2021). As Reside et al. (2019a) state, isolated populations on the edges of suitable habitat need to be identified as these populations are the most likely to be able to adapt to climate change.

The study of different frog species can benefit humanity in many ways. We can learn a lot from the structure or secretions of frogs and these data can then be used in industries such as medical research (Xie 2018). As an example, frog species could benefit us through learning of the structure of their adaptations. *Taudactylus* species are known to secrete several, unique, highly active peptides that are currently understudied and these could have benefits in medical research areas such as antibiotics (Clarke 2006). Similarly, the torrent frogs of the *Litoria* genus could improve the integrity of adhesives as the toe pads of torrent frogs have been found to have more tensile strength than those of geckoes (Iturri et al. 2015).

This study is significant because there are many areas of the Wet Tropics that have not been searched for these particular frog species and it is thought that these frogs could living undiscovered as areas of the Wet Tropics have been overlooked in favour of the wetter rainforest areas (Hoskin & Puschendorf 2014). Many of these areas have also never been surveyed for vertebrates (Hoskin & Puschendorf 2014) and this study will narrow the area of focus in order to determine the most optimal areas to search, the most likely areas for frogs to be hiding and the habitat features to look for. This will define the conservation status and aid in management strategies. Of all the VIPS' in the Wet Tropics, there are only four species that qualify on all four criteria and two of these are *Taudactylus acutirostris* and *Taudactylus rheophilus* (Alford & Rowley 2007; WTMA 2016).

1.4 Aim and Objectives

The aim of this thesis is to discern the spatial distribution of four critically endangered frog species endemic to Far North Queensland in order to clarify their conservation status and understand potential threats to their distribution. The following specific objectives are presented below:

a) To model and map the spatial distribution of the four critically endangered frog species endemic to Far North Queensland

b) To identify and assess the current and future threats to these species, focusing on climate change in 2040 and 2080 using SSP126

c) To develop strategies and recommendations for the conservation of these species

The expected outcome of this study is that areas of previously unsuspected habitat will be imminently seen as suitable. This suitable habitat is expected to decrease with time and with less optimistic Shared Socioeconomic Pathways (SSP's). This study sought to answer the following research questions:

a) What is the most suitable elevation for each species?
b) How does a change in temperature affect these species?
c) Does land use affect the distribution of these frogs?
d) Is distance to water source the most important factor?
e) Is there an area that is suitable for all four frog species?

1.5 Scope and Limitations

This study focused on modelling potential areas of suitable habitat within the Wet Tropics for four species of critically endangered frog. This was conducted through the use of Geographic Information Systems (GIS) and the use of historical sightings to determine preferred environmental conditions. The study area was the Wet Tropics bioregion of Far North Queensland (FNQ), stretching from Cooktown in the North to Townsville in the South coming 85km inland to Atherton. This study was limited by the number of frog sightings available, the assumptions and limitations that come with a small selection of records such as habitat preferences and environmental conditions. The study was also limited by the environmental datasets that are available.

1.6 Organisation of the Dissertation

This thesis is divided into six main chapters.

The **first** chapter is the introduction to the thesis and covers the reasons behind the topic of the thesis. This is where the significance of the study is covered and the scope and limitations explained. The statement of the problem and the research gaps are outlined here. This chapter gives an idea of the topic of the thesis.

The **second** chapter is the literature review which covers all the available data which has been collated for the species of the study. It details the specific characteristics of each genus and species and examines the threats they face.

The **third** chapter is the methodology, this is where the methods of collecting data are explained and analysed. The sources of data, the methods of using the data and how the data is used is covered in this chapter. The verification of the data is also covered.

The **fourth** chapter details the current distribution of the species of interest in this study and gives background information on how spatial distribution is determined. This chapter highlights the results of the modelling to identify areas of suitable habitat. This is where the current knowledge of the distribution of the frog species is displayed and the history of species distribution modelling (SDM) is explained.

The **fifth** chapter builds on the information learnt in chapter four by discussing the impacts of climate change to the current distribution and what this will mean for the future of the species examined in this study. Two different emission pathways are used to show the variance in spatial distribution with different emission strategies.

The **sixth** chapter outlines the recommendations for future research on each of these species and determines what needs to be done in order to allow these species a chance at survival. This is where the outlines for practical application are mentioned.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

In Australia, frogs inhabit every environment, from swamplands to mangroves, to arid zones and inner cities (Clulow & Swan 2018). There is no area that is amphibian free. Frogs are an essential part of these habitats as they are direct contributors to ecosystem health (NSW Government 2020) As adults, frogs regulate the water and the environment by removing disease carrying mosquitoes and other small insects (Kriger 2017). As tadpoles they filter water and remove harmful algae from waterways while providing an important food source for many animals (de Almeida et al. 2015). Frogs are also good for use as an environmental indicator (NSW Government 2020). The better the environment, the more frogs that will be around. The unhealthier the environment becomes, the less frogs there will be (NSW Government 2020).

Frogs are understudied and underappreciated, despite their necessity (Rojas 2017). Australia is known, globally, as having a wide variety of frog species, yet there is little data to be found on specific species. Only a handful of the 246 species and subspecies that are currently recognised to inhabit Australia are fully studied. Despite the high abundance of local endemism within Australia and the Wet Tropics, the level of taxonomic knowledge is highly inadequate for many species (WTMA 2016) and many species urgently require research.

These 246 species and subspecies are grouped into three families with each having a distinct style (Clulow & Swan 2018). The *Litoria* frogs are the tree frogs: the only frogs which can grip and climb. The second group are the *Limnodynastidae*: the foam nesting ground frogs, characterised by a distinct foam dome surrounding the eggs. The third family is the *Myobatrachidae*: the ground frogs which do not produce a foam layer with their eggs. Each family is well represented yet understudied. The Wet Tropics has 51 of the 246 species found in Australia, with at least 20 of these species locally endemic (Hero & Morrison 2015).

Frog identification in Australia commenced not long after the Europeans first arrived in the late 1700's and early 1800's yet little progress has been made since this research was initiated (Cogger 2014; Pearson 2018). The first study on a frog in the Wet Tropics was more than a century after the first frog was described in Australia and there are still major research gaps within nearly every species of frog found in Australia. Many frogs do not have an accurate or up to date spatial distribution map and many are yet to have their life histories described. Current species extinctions are 1000x the background extinction rate (Reside et al. 2019a), making species distribution mapping even more important. 50 of the 246 species currently recognised in Australia are classed as threatened or extinct (Hero et al. 2006; Hero & Morrison 2015; Clulow & Swan 2018). Habitat loss or modification is associated with the decline of 23 of the 50 species (46%) (Hero et al. 2006). Since the first frog was described in the Wet Tropics, a further six species have been discovered, adding to the list of research that needs to be done and research gaps that need to be filled (Australian Geographic 2017).

The widespread decline in frog species is thought to have started in Southern Queensland and headed North to reach FNQ in the mid 1980's (Trenerry et al. 1994) where it caused the decline of six stream dwelling frog species (Trenerry et al. 1994; Hero & Morrison 2015). While the cause of these declines is still unknown they are not thought to have been from collecting species for research, low rainfall, natural disasters such as floods or from roadkill (Richards et al. 1993). It is also thought that acid rain is not a leading contributor although resistance levels are not known (Richards et al. 1993) as these species have not been tested.

2.2 *Litoria* Frogs

Frogs classed as *Litoria* are those that are commonly known as 'Tree Frogs'. They are the frogs that have the ability to climb trees and cling to surfaces other frogs cannot. Within the *Litoria* species there are a number of guilds based on habitat, reproduction, habitat use, temporal activity, microhabitat and body size (Williams & Hero 1997). This study focuses on the torrent frog guild of which there are six members (Clulow & Swan 2018). Torrent frogs are so named due to their existence in the fast-flowing waters, such as the torrents and rapids associated with waterfalls. Five of the six members of this guild are locally endemic to the Wet Tropics (Cogger 2014) and all six are severely lacking in baseline knowledge and up to date research (Clulow & Swan 2018). Two of the torrent frogs are used in this study and these are *Litoria lorica* and *Litoria nyakalensis*. Both these frogs have very low recorded population densities (IUCN 2021) and both species declined during the 1980's and 1990's. These species were thought to be extinct from their known distribution until *Litoria lorica* was found outside its range in 2008 in areas it was not previously thought to inhabit. This gave hope that populations of other species thought to be extinct still exist.

Litoria frogs are unique among frogs as they have the ability to grip wet surfaces and climb rocks and trees. Torrent frogs have an enhanced grip even when compared to other *Litoria* frogs and can grip wet rocks within waterfalls (Iturri et al. 2015). This is due to a unique, elongated feature of their toe pads which allows them to create a significantly higher degree of friction when compared to all other arboreal species. This friction is also created by a secretion of mucus into the pad substrate gap (Langkowski et al. 2018). This mucosal secretion means these frogs have a requirement for increase mucus drainage and this is achieved through unique surface patterns of the toes (Iturri et al. 2015). The torrent frogs have evolved this ability through evolution and necessity due to their chosen environment. The strength of the toe pads on *Litoria* species has been shown to have a higher tensile strength than those of a gecko. As geckoes toe pad structure are currently used as a model for the creation of adhesives, the unique features of the toe pads of the torrent frogs would greatly increase the functionality of the adhesives as well as benefit other industries.

There is a significant lack of knowledge and research on the torrent frogs. To date, there have only been five papers written on torrent frogs with the first having only been in 1995. The last study was conducted in 2018 and this followed the study of 2015 which closely examined the toe pads of torrent frogs and how the structure can be applied to the adhesive industry (Langkowski et al. 2018).

2.2.1 Litoria lorica

Litoria lorica is a 2 - 3cm frog that, for many years, was thought to only inhabit the areas of the Wet Tropics above 400m elevation but with the rediscovery of a population below this elevation this assumption has been revised. It is one of only two frogs that has been rediscovered in the streams of the Wet Tropics (Marshall 1998). Its common name is the Armoured Mist Frog (Clulow & Swan 2018) and it is known from only a handful of sightings in the Wet Tropics region (Belbin 2011). It is currently regarded as stable, although with extremely low population numbers. Six studies over 2008 and 2009 show the population levels as 3.25 – 8.75 individuals per 100 metres (Puschendorf et al. 2011).

A second population was established in 2014 in similar habitat across environmental barriers to give the species increased chance to prosper (Hoskin & Puschendorf 2014).

The individual frogs of *Litoria lorica* (Figure 2) are very similar in appearance to *Litoria nannotis* with which it shares distribution and habitat preferences (Clulow & Swan 2018) but can be discerned by its visible size difference and darker colouring. They can also be differentiated by their call. The males of *Litoria lorica* have never been recorded to have a call despite there being repeated attempted of breeding in captivity. *Litoria nannotis*, however, has a call of a series of short growls (Clulow & Swan 2018).

Figure 2: Litoria lorica (Litjens 2021)

The sightings of *Litoria lorica* have historically come from the northern end of the wet topics (Figure 2) with most of them coming from the areas of lower elevation towards the coast. There are few individual sightings of *Litoria lorica*, adding to the difficulty in determining spatial distribution. In total there are 18 individual records for *Litoria lorica* despite it being regarded as stable in its known populations.

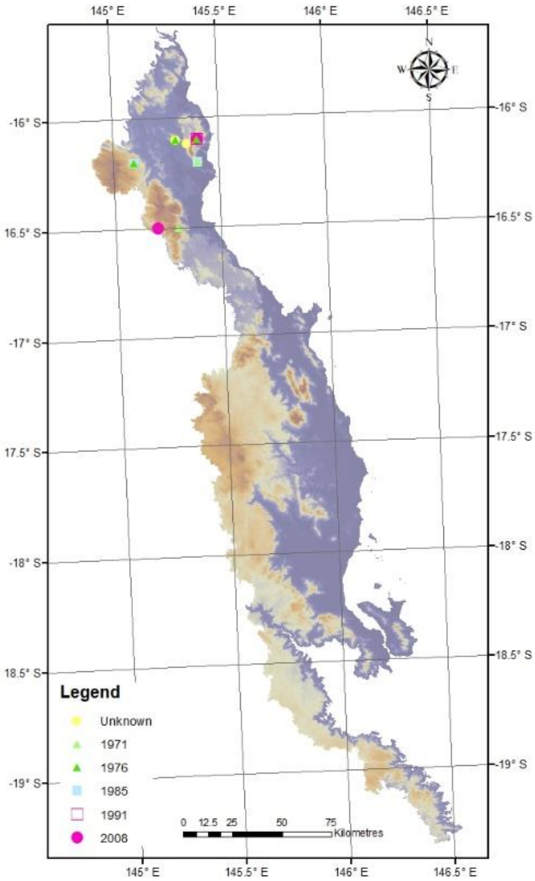

Figure 3: The historical sightings of Litoria lorica. The symbols show the decade in which the sighting was taken. The darker areas represent higher elevations. The darker the area, the higher the elevation.

2.2.2 *Litoria nyakalensis*

Litoria nyakalensis (Figure 5) is also a 2–3 cm long frog, known to previously be well distributed across the tops of mountains throughout the Wet Tropics (ALA), including Mt Bellenden Ker. There are 164 verified sightings of this species over multiple years and as Figure 3 shows, there are multiple records across the area with the majority being along the western side on the darker areas representing the higher elevations of the Wet Tropics.

Litoria nyakalensis is commonly known as the Waterfall Frog (Clulow & Swan 2018) but no individuals of this species have been recorded since 1991 (Marshall 1998). The call has been described as a small chirp that is distinctive from other species in the area (Clulow & Swan 2018).

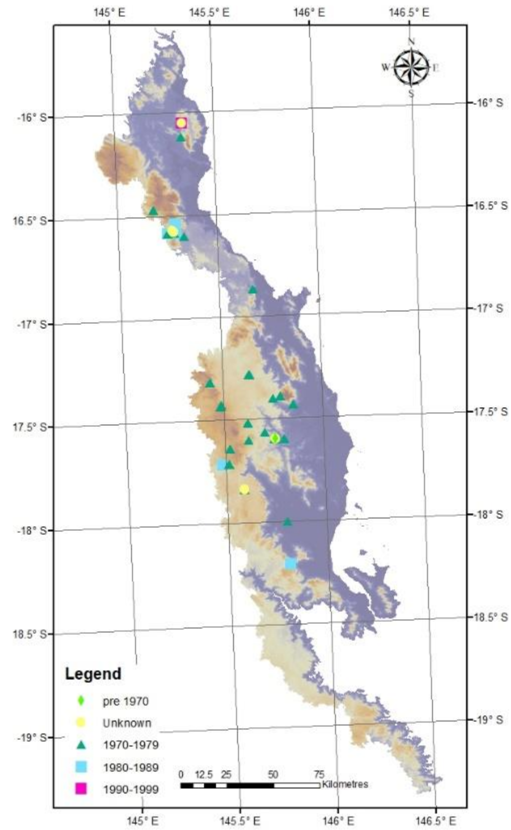

Figure 4: The historical sightings of Litoria nyakalensis. The symbols show the decade in which the sighting was taken. The darker areas represent areas of higher elevation. The darker the area, the higher the elevation.

Litoria nyakalensis is visually distinct from other frogs in the area due to the pink flush on its chest and limbs that characterise the species (Clulow & Swan 2018). It can also be distinguished by its small size when compared to other species and its lack of patterning such as is seen on *Litoria lorica* (Department of Climate Change; Energy; Environment and Water 2022d).

Figure 5: Litoria nyakalensis (McDonald 1997)

2.2.3 Habitat and Distribution

Torrent frogs are predominantly known to be rainforest species that inhabit the fast-flowing water associated with high altitudes. They are found with the torrents created by waterfalls in areas of high rainfall such as those seen in the Wet Tropics. All six species of torrent frog currently identified within Australia live in the Wet Tropics with five of the six restricted to its boundaries. Within the torrents, *Litoria lorica* is known to inhabit the small pools and shallows of the fast flowing streams but is thought to prefer granite boulder streams (Clulow & Swan 2018). *Litoria nyakalensis* is associated with rocks and boulders with the rapids of fast flowing streams where it completes its entire life cycle. Food is taken directly from the water flowing past and shelter is sought under and between rocks (Haas & Richards 1998).

2.2.4 Life History

Torrent frogs are unique in their chosen habitat and life history. These frogs live and breed with the rapids and torrents of fast flowing streams. The eggs of *Litoria nyakalensis* are laid in clumps which are attached to rocks within the torrents while the tadpoles of *Litoria nyakalensis* have evolved specialised mouthparts that allow them to cling to the boulders within the rapids and torrents (Richards 2002). This is due to the gills present on the tadpoles and the highly oxygenated water of riffles (Richards 2002). The young are able to filter the water streaming past thus allowing them to feed while clinging to the sides of boulders. It has been thought that tadpoles of *Litoria nyakalensis* burrow into sand when torrent become too strong but there is no evidence to support this (Richards 2002). The tadpoles are highly specialised to thrive in their chosen environment (Haas &

Richards 1998) and this leads to delayed lung development in metamorphosed frogs. Due to the high volumes of their chosen habitat, the adults have developed a unique and specialised method of communicating, they have been observed to have used hand waves to communicate.

There is little data available for the life history of *Litoria lorica* and no information exists on breeding season, reproduction timing or egg deposition (Puschendorf et al. 2011; Department of Climate Change; Energy; Environment and Water 2022a). *Litoria lorica* lays eggs in shallow ponds and the tadpoles have modified their mouthparts into large suctorial discs which allow them to cling to and forage on the algae on rocks of fast flowing streams (Hoskin & Hero 2008; Puschendorf et al. 2011). The adults of *Litoria lorica* are known to sun themselves on rocks but little else is known about their life history.

2.3 *Taudactylus* Frogs

Taudactylus frogs are a range of frog species within the genus *Taudactylus* and are direct descendants of frogs that were around during Gondwanan times. They are recognised as having an ancient lineage and are listed as Very Important Protected Species (VIPS) by the Wet Tropics Management Authority (WTMA). Two species in the *Taudactylus* genus are part of a group of only four species that qualify on all four criteria for the listing (WTMA 2016). Five of the six *Taudactylus* frogs species recognised are classed as threatened (Hero & Morrison 2004) in contrast to other frog species where the phylogenetic relationship is more poorly understood (Marshall 1998). All *Taudactylus* frogs are small frogs, averaging between 2 – 3 centimetres (Cogger 2014) and are restricted to the upland rainforests and the associated wet sclerophyll creeks that occur along the eastern coast of Queensland (Richards et al. 1993).

Taudactylus frogs are small, cryptic species divided into two groups. The first group is the Tinkerfrogs. This group contains *Taudactylus acutirostris* and is so named due to the sound that the frogs within this group emit. The second group is the Day frogs, called this because of the unusual habit of being active during the day. This second group is that to which *Taudactylus rheophilus* belongs. These frogs are divided this way based on habitat selection, activity patterns and call characteristics (Clarke 2006). These two species are both endemic to the Wet Tropics and both have not been seen since the early

90's. Overall *Taudactylus* species are found along the eastern coast of Queensland in upland rainforests and wet sclerophyll creeks (Richards et al. 1993).

Taudactylus frogs are defined by their T-shaped phalanges and are anatomically distinct from other genera (Tyler et al. 1993). They are known to be cryptic frogs that appear sporadically in different locations (Freeman 2003) and have been known to travel long distances away from water sources during wet weather (Department of Climate Change; Energy; Environment and Water 2022c) making it hard to define their distribution.

2.3.1 Taudactylus acutirostris

Taudactylus acutirostris is known as the Sharp Snouted Day Frog and has not been seen in the wild since 1994. There is little hope left for its survival despite two similar, absent species being found in the swift waters and associated seepage areas of the Wet Tropics streams in the 1990's (Marshall 1998; Hoskin & Hero 2008). It is known to be cryptic and tends to call only during rain events (Clarke 2006) making it a hard species to locate. *Taudactylus acutirostris* is a small frog of 2 – 3 cm in length that blends well within its environment. This frog is known from 479 individual records across the Wet Tropics (Belbin 2011). It is currently declared extinct in the wild in Queensland but this is based on outdated evidence using manual searches (Clulow & Swan 2018; Department of Climate Change; Energy; Environment and Water 2022c). Under the IUCN listings it is still listed as critically endangered pending more research into whether there are still undiscovered populations remaining (Department of Climate Change; Energy; Environment and Water 2022c). It is thought this species might be surviving in small, isolated population across the Wet Tropics (Hoskin & Puschendorf 2014).

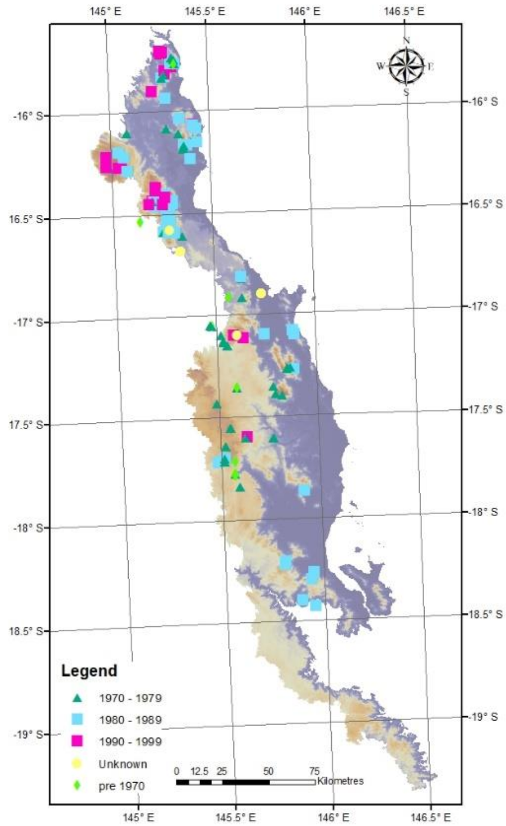

Figure 6: The historical sightings of Taudactylus acutirostris. The symbols show the decade in which the sighting was taken. The darker areas represent areas of higher elevation. The darker the area, the higher the elevation.

Taudactylus acutirostris can be easily distinguished from all nearby frogs, including *Taudactylus rheophilus*, by its distinctly pointed snout and dorsolateral skin fold (Clulow & Swan 2018) and due to *Taudactylus* frogs being anatomically distinct from other genera. The only other *Taudactylus* frog in its distribution is *Taudactylus rheophilus* to which its colouring differs.

Figure 7: Taudactylus acutirostris (Cogger 1997)

2.3.2 Taudactylus rheophilus

Taudactylus rheophilus (Figure 8) is commonly known as the Northern Tinker Frog and has not been seen since in numbers since 1991 (Marshall 1998). The last recorded sighting was in 2000 after it was rediscovered on Mt Bellenden Ker and 11 individuals were located (Freeman 2003; Hoskin & Hero 2008) but few surveys have been done since this time and no paper has incorporated distribution modelling into its surveys. Researchers have relied on visual identification through manual searches. This method often leads to disrupted habitat and a degraded environment (Freeman 2003). The largest number of sightings of *Taudactylus rheophilus* are from Mt Bellenden Ker (Figure 9) with the Carbine Tablelands, Lamb Range and Thornton Peak all known sites. Mt Bellenden Ker is considered the wettest place in Australia, creating the idea that high precipitation was important for this species (WTMA nd). *Taudactylus rheophilus* comes in a variety of colours ranging from grey to light brown to dark brown. *Taudactylus rheophilus* is listed as critically endangered by the EPBC as well as by the IUCN (Department of Climate Change; Energy; Environment and Water 2022b) and requires updated information to ensure the accuracy of this listing. This species is particularly cryptic (Hoskin & Puschendorf 2014) making locating populations extremely difficult and there is a reasonable chance that there are still extant populations of this species persisting in small numbers throughout the Wet Tropics.

Figure 8: Taudactylus rheophilus (Mahoney 2000)

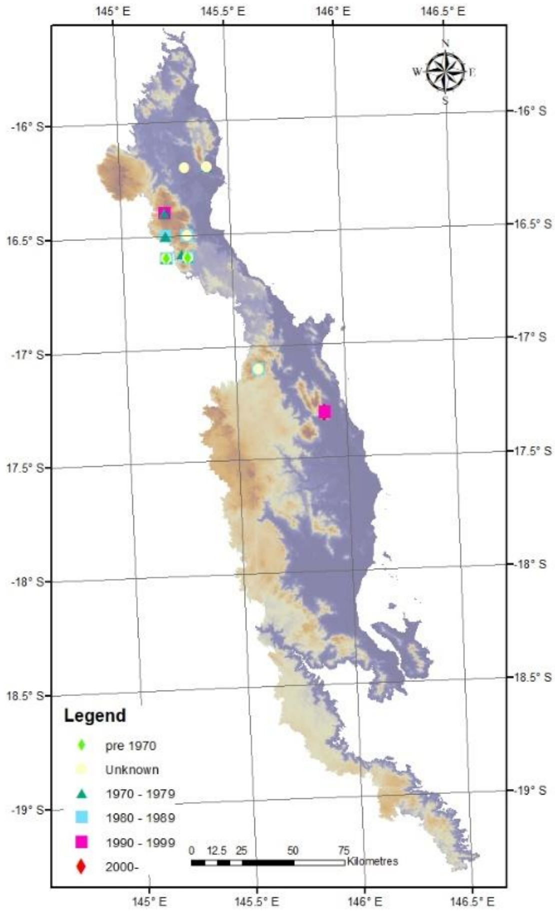

Figure 9: The historical sightings of Taudactylus rheophilus. The symbols show the decade in which the sighting was taken. The darker areas represent areas of higher elevation. The darker the area, the higher the elevation.

2.3.3 Habitat and distribution

There are six species of *Taudactylus* spread across Queensland. *Taudactylus acutirostris* and *Taudactylus rheophilus* are the only two *Taudactylus* species confined to the Wet Tropics. *Taudactylus acutirostris* is known from the tops of mountains (Figure 6) within the Wet Tropics and has sporadically been seen on different mountaintops at different times. This has made it hard to determine the status of extant populations. *Taudactylus acutirostris* has been known from upland rainforest creeks and is thought to only inhabit the area around Mt Bellenden Ker, the highest mountain in the Wet Tropics (Clulow & Swan 2018).

This species lives in rocky streams of upland rainforests, making good use of the rocks and logs found within and beside streams of this area. It has previously been found by the turning over of these rocks and logs although this method is not recommended due to its habit of destroying the environment in the name of research (Freeman 2003).

2.3.54 Life History

There is little known about the life history of both *Taudactylus* frogs and there inadequate knowledge in both the habitat and reproductive requirements of *Taudactylus* species (Clarke 2006). *Taudactylus acutirostris* has been known to call from in and beside streams in the wet season and eggs have been recorded as laid in the shade amongst rocks within streams (Clulow & Swan 2018) although metamorphosed frogs have never been seen. Currently, all *Taudactylus* species are thought to lay their eggs and attach them to the underside of rocks in shallow ponds of slow moving or still water in Spring and Summer (Clarke 2006) but it is possible that this is not the case with either *Taudactylus acutirostris* or *Taudactylus rheophilus*. It has been noted that tadpole populations in other species are size structured most of the year (Richards 2002).

2.4 Threats

There are many threats which are hypothesised to affect the distribution of frog species but there is not always evidence to support or refute these hypotheses. Many species are also threatened by multiple stressors within a single environment which interact to accelerate declines in a population (Reside et al. 2019a). Environmental factors such as rocky gorges, stream cover and canopy cover can cause or reduce the impact of stressors (Reside et al. 2019a). For instance, reduced stream cover can increase solar radiation, increase the temperature and reduce the amount of shelter available. These higher temperatures and radiation can reduce pathogen prevalence but reduce the amount of shelter available and increase the amount of water required for survival (Reside et al. 2019a). The variables change with and within the environment and more study is required to fully understand the threats to frogs and their habitats. The factors that threaten almost half of all frog species in decline remain unknown (Clarke 2006) although from the literature it appears to be common consensus that climate change is the major threat (Nakicenovic et al. 2000; Hero & Morrison 2004; Clarke 2006; Parry et al. 2007a; Sinclair et al. 2012; Hero & Morrison 2015; WTMA 2019) followed by chtytridiomycosis (Woodhams & Alford 2005; Australian Government 2006; Bosch et al. 2011; Murray & Skerratt 2012; Puschendorf et al. 2013) with multiple minor stresses.

2.4.1 Climate Change

Climate change is the changing of a climate to outside normal parameters for a particular region at a particular time (WTMA 2019). Climate change is more than the temperature simply going up. Climate change will result in more extreme weather (higher highs and lower lows) as well as altered biological schedules and life histories and will create less favourable conditions for those species that evolved to thrive in a stable climate (BOM & CSIRO 2020) such as the four species used in this study. The Wet Tropics is recognised as having extreme sensitivity to climate change (BOM & CSIRO 2020). Streams in the Wet Tropics are characterised by variability in their spatial and temporal aspects (Richards 2002) and this temporal variability is connected to the abiotic factors of the region such as discharge during the dry season versus the wet season and the presence of cyclones (Richards 2002).

Approximately 97% of the species of the Wet Tropics that are found in higher elevations will be impacted by climate change (Reside et al. 2019b), therefore species and their habitats need to be actively managed in order to mitigate the effects of climate change species will face (Reside et al. 2019a) with or without significant mitigation efforts.

2.4.2 Habitat Loss

Habitat suitability can be defined differently for each species. In the Wet Tropics, habitat suitability is often defined by moisture availability and cool conditions (Reside et al. 2019a).

The Wet Tropics was declared a World Heritage Area in 1988 (WTMA nd) and parts are continuously being declared protected areas (WTMA 2015), hopefully allowing them protection from future activities that that would see the demise of its forests, such as logging. The modification of these habitats and other anthropogenic activities is the leading cause of emerging infectious diseases (Murray & Skerratt 2012) and clearing of low lying rainforest has resulted in reduced ability and possibility of species translocating to areas with greater protection against disease (Richards et al. 1993). Diseases are a constant risk in environments with cooler climates, such as mountainous areas and much harder to fight in these environments.

2.4.3 Chytridiomycosis

Chytridiomycosis is one of the leading causes of frog death and decline in Australia (Murray & Skerratt 2012) and is believed to be the leading cause of the decline of the frogs of the Wet Tropics (Trenerry et al. 1994) in the 1980's and 1990's. Chytridiomycosis affects populations throughout the cool, mid- and uplands areas (Reside et al. 2019a) in which pathogens tend to thrive (Puschendorf et al. 2011).

Chytridiomycosis is caused by the bacteria *Batrachochytrium dendrobatidis* (Bd) (Puschendorf et al. 2011) and can infect a frog at any life stage (Murray & Skerratt 2012). The limitations of Bd are currently being explored in order to determine potential refuges for affected species (Reside et al. 2019a). As of 2012 only half of all frog species in Australia had been tested for Bd with more than 60% of the species tested returning positive results (Murray & Skerratt 2012).

The impacts of chytridiomycosis and other such diseases on populations of wild animals, including frogs, is strongly influenced by cofactors such as pathogen tolerance, habitat preferences of vectors and reservoir hosts (Bell et al. 2018) with areas of the uplands above 300m the most affected. Temperature is a key factor in the survivability of frog species against chytridiomycosis (Bell et al. 2018) with higher temperatures of lower elevations stopping Bd from reaching lethal levels (Puschendorf et al. 2011). Species with broader environmental gradients are more resilient against disease (Puschendorf et al. 2011) as they have a larger distribution in which to find refuge. The availability of patches of open canopy which give frogs the opportunity to sunbathe has been shown to be a key in reducing the effects of chytridiomycosis (Greenspan et al. 2017).

Recent studies have shown that a species once decimated by chytridiomycosis has started to increase its population size, leading to the hypothesis of naturally derived antibody resistance (Hollanders & Newell 2022) and gives hope to other species decimated by chytridiomycosis. More studies are required to fully understand the situation.

2.5 Research Gaps

2.5.1 Litoria Research Gaps

As very little is known about these frogs there are many research gaps. Breeding has not been documented for *Litoria lorica* despite attempts at captive breeding (Reside et al. 2019a) and it is likely that the environmental breeding requirements needed for successful mating have not been identified. Any change, intended or not, to the environment can cause populations to fluctuate through stress. Any population that is already small is likely to suffer detrimentally and potentially go extinct (Murray & Hose 2005). The distribution of these species is also a major research gap which then leads to more research gaps within habitat requirements, environmental tolerance and threat mitigation. It is known that Litoria frogs use a hand wave system to communicate (Clulow & Swan 2018) due to the high noise volume of their chosen environment but this has never been properly documented.

The lack of data on their distribution is a significant knowledge gap and closing this gap will allow for other research gaps to potentially be closed. For example, knowing the distribution will allow for research into threat management and will help to determine how environmental factors influence distribution. The distribution of torrent frogs has historically been over looked with most papers written on *Litoria nannotis* alone, a similar but distinctly separate species that is threatened but stable (Clulow & Swan 2018). It has only been in recent years that effort has been made to determine their potential and actual extent. Despite these efforts, this remains a research gap for torrent frogs.

2.5.2 Taudactylus Research Gaps

Few studies have been done on the individual species of *Taudactylus*. Much of the information that is observed in one species is assumed in species where the same information has not been recorded (Clarke 2006) but these is no evidence. For example, with *Taudactylus acutirostris*, breeding has been observed from November to January, eggs are known to be laid under rocks or overhanging branches and tadpoles are known to be aquatic but nothing is known of metamorphosed frogs, the breeding and habitat requirements or sex ratios (Clarke 2006). *Taudactylus rheophilus* has similar issues. Gravid females have been found, therefore the eggs are known, but no information is available on where the eggs are laid, tadpoles have not been seen and the habitat and breeding requirements are still unknown. Where this information is lacking it has been taken from other, similar species where the information is known and then assumed to be the same (Clarke 2006). In this case what is unknown in *Taudactylus acutirostris* is taken from *Taudactylus rheophilus* and vice versa.

Species declines are consistently found to be strongly correlated with the size of the species geographic range as well as the body size of the species (Murray & Hose 2005). It has also been noted in other Wet Tropics species that those in decline are those that breed in streams, and are endemic rainforest species that are prone to low fecundity (Murray & Hose 2005). Any change can be catastrophic for a population that is low before the change. Unexpected changes to the biotic and abiotic environment are potential extinction events for species with low population levels (Murray & Hose 2005). *Taudactylus* frogs secrete unique peptides that could benefit industries if studied for antibacterial or other properties (Erspamer et al. 1975).

As very little is known about these frogs there are many research gaps. Breeding has not been documented for *Litoria lorica* despite attempts at captive breeding (Reside et al. 2019a) and it is likely that the environmental breeding requirements needed for successful mating have not been identified. Any change, intended or not, to the environment can cause populations to fluctuate through stress. Any population that is already small is likely to suffer detrimentally and potentially go extinct (Murray & Hose 2005). The distribution of these species is also a major research gap which then leads to more research gaps within habitat requirements, environmental tolerance and threat mitigation.

The lack of data on their distribution is a significant knowledge gap and closing this gap will allow for other research gaps to potentially be closed. For example, knowing the distribution will allow for research into threat management and will help to determine how environmental factors influence distribution. The distribution of torrent frogs has historically been over looked and it has only been in recent years that effort has been made to determine their potential and actual extent. Despite these efforts, this remains a research gap for torrent frogs.

2.6 Summary

There are few historical records available for *Litoria lorica* and *Taudactylus rheophilus* while there is an abundance of records for *Litoria nyakalensis* and *Taudactylus acutirostris*. Despite this, the literature shows that there are large knowledge gaps for each of these frogs and more work is crucial to understanding their life histories, distribution and habitat requirements. As shown above, these frogs have been known to inhabit different areas of the Wet Tropics and more research efforts are needed investigating the reasons behind this difference.

The major threat to these frogs is climate change with modelling required to understand the impact this will have on future distribution. Chytridiomycosis is also a significant threat, but testing needs to be done to determine whether these frogs have resistance or are susceptible.

This study will fill knowledge gaps on potential distribution and create the foundation for future research and conservation on these species. It will investigate the effect of future climate change scenarios and how this differs from the current distribution patterns.

CHAPTER 3: METHODOLOGY

3.1 Introduction

Species distribution modelling is a technique that incorporates a variety of biotic and abiotic factors and can be used to determine a wide variety of elements of species distribution (Hijmans & Elith 2021). It can be used to calculate the most suitable habitat for a species, the temporal change in a species distribution or the current spatial distribution for a particular species and aids in the implement of essential conservation strategies (Swan et al. 2021). The factors involved change with the species that is being modelled and reflect the factors that influence the distribution of the species in question. Most often the model will involve environmental and climatic factors along with the sightings of the species. A computer algorithm, such as MaxEnt (Phillips et al. 2017), is then used to model the suitable habitat. The modelling of a change in distribution can be positive (the distribution of the species is seen to increase) or negative (the distribution of the species decreases). The modelled distribution can change the direction of future study and allow the prioritisation of key areas or an alteration in practices. This study uses Geographic Information Systems (GIS) to create a Species Distribution Model (SDM) for four frog species using all known geographic sightings of the species that have occurred. The figure below (Figure 10) outlines the basic steps to create an SDM.

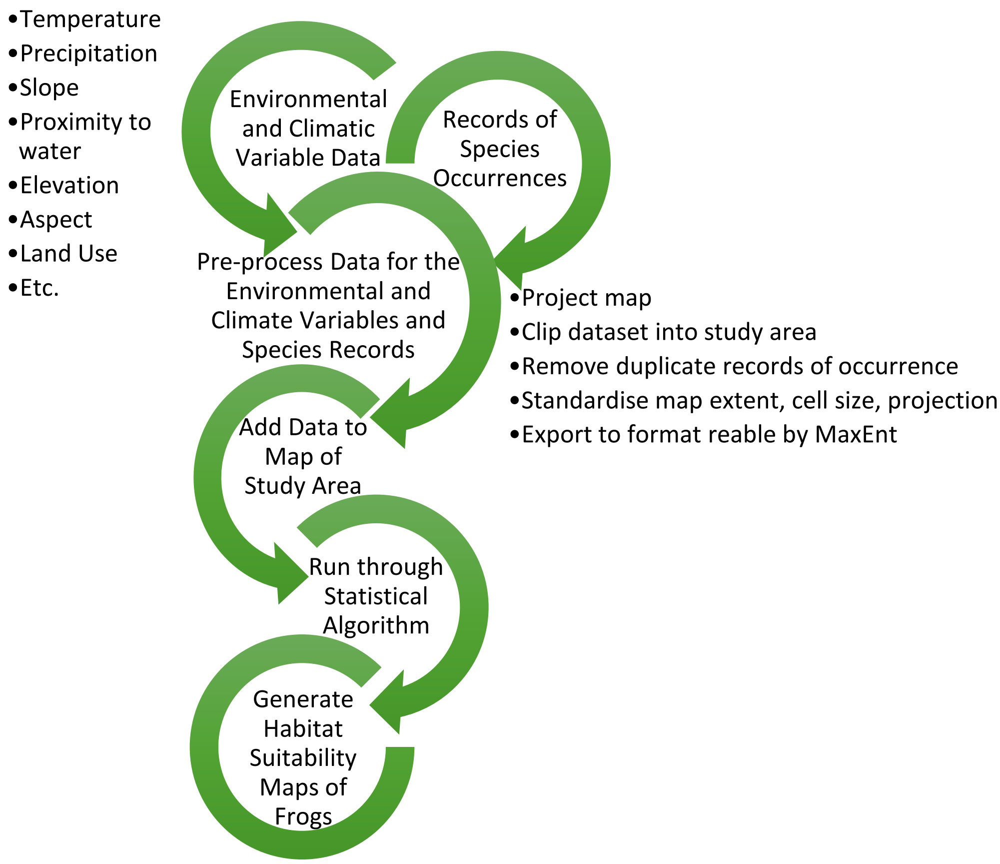

Figure 10: A general overview of species distribution modelling used in this study

SDM's have been around for centuries with origins in the 1800's. Today, SDM's are a little more sophisticated and use a wider variety of data to predict distributions. SDM's are widely used in fauna studies (Fournier et al. 2017) to determine species predictions as they can be used to high accuracy. Models that use a statistical algorithm (such as MaxEnt), are shown to have higher degree of accuracy than those that use another method. Much of the data used in these models is based on assumptions and opportunistic recordings (Puschendorf et al. 2013). These assumptions include that the species is at equilibrium and does not have limitations to dispersal.

Predictor selection continues to be a significant issue in determining relevant variables as their importance relies on a correlation between the environmental variables and the ecological variables that drive the spatial distribution of a species (Fournier et al. 2017), although this can be alleviated with expert knowledge and variables key to the selected species.

3.2 Study Area

The Wet Tropics is an environmentally significant bioregion located on the north eastern coast of Queensland, Australia. It is a 450km long stretch of coastline between Cooktown and Townsville in the far north. It also stretches 85km inland to the Atherton Tablelands (Hoskin & Hero 2008). It also includes a section of the marine environment (Alford & Rowley 2007). The Wet Tropics stretches for 19,929km^2 and encompasses 0.26% of the Australian mainland (Alford & Rowley 2007; WTMA 2016) and rises to 1700m above sea level (Pearson 2018). It consists of tropical rainforests, rugged mountainsides and tranquil valleys as well as rocky gorges and waterfalls (Pearson 2018). To the east, it is bordered by the Pacific Ocean with its fringe coral reef and to the west by grasslands. The existence of fringe coral reef in close proximity to coastal rainforest is rare worldwide (DWAE 2021) and it is an area of high local endemism and biodiversity. The Wet Tropics has been declared an area of significance, is on the World Heritage Area index and has an incalculable value for science (WTMA 2016).

The climate of the Wet Tropics has been stable for millennia with high seasonal rainfall (Alford & Rowley 2007), creating a secure biosphere and allowing for animals and plants to thrive in a world that no longer exists for much of the planet (Alford & Rowley 2007). It is now the only place on Earth that ancient plants and animals can still thrive, millions of years after they died out over the rest of their distribution. It is for this reason that the Wet Tropics has been regarded as both a living museum and a crater of life.

In 1988, the Wet Tropics was declared a World Heritage Area (WHA). Prior to this, the area was heavily logged for timber (WTMA 2015) resulting fragmentation across parts of the Wet Tropics. As of 2007, 65% of the Wet Tropics was part of a Protected Area (PA) and this has been steadily growing each year (Alford & Rowley 2007). The people of FNQ understand the role that the Wet Tropics plays and are connected to nature, rely upon its services and benefit from them (WTMA 2015) with the Wet Tropics home to the largest number of ecotourism operators worldwide. $2.6 billion is associated with ecotourism in the Wet Tropics each year.

There is a distinct wet and dry season across the Wet Tropics. The wet season stretches from October to March (Pearson 2018), making the dry season April to September with the highest rainfall in November to March (Pearson 2018). While covering less than 1% of the mainland, it contributes to more than 7% of Australia's runoff (Pearson 2018).

3.3 Data Acquisition

The data used in this study was acquired from many different sources. There were three types of data that were required such as data for the historical sightings of frogs, the environmental variables and the climate data. The first of these, the historical frog sightings were downloaded from the Atlas of Living Australia (ALA) and the Global Biodiversity Information Forum (GBIF) for all four species and included all historical, verified sightings of these species. The GPS points attached to each of the records were taken and put into a map in ArcGIS to show the location in which the records were taken. Duplicate records were excluded but no individual sightings were removed.

The boundaries of study area were taken from the biogeographic regions dataset from the Department of Environment and Science (DES) to ensure the correct boundaries of the Wet Tropics were used. These boundaries were then used to clip (subset) each succeeding dataset.

Environmental factors were analysed for their applicability, based on the needs of the frogs, then chosen and downloaded. For this study the selected environmental factors were elevation, aspect, slope, distance to water, land use and land cover. The slope, elevation and aspect were calculated from the Digital Elevation Model (DEM) which was downloaded from the QSpatial data portal (https://qldspatial.information.qld.gov.au/catalogue) for the whole of Queensland and clipped to the study area. This dataset is based on Department of Resources information.

The distance-to-water variable was obtained from the land cover data. It consisted of the water cover layer being extracted and from this the Euclidean distance was derived.

The land cover dataset was created by ESRI and was downloaded from the ESRI website (https://livingatlas.arcgis.com/en/browse/) and is based on 2020 Sentinel data. The land use layer was downloaded from the QSpatial website) and is the result of data obtained by Department of Agriculture and Fisheries (DAF). Of the three land use layers available, 'secondary' land use types were used due to their suitable level of aggregation. The 'primary' land use was determined to be too broad while the 'tertiary' land use classes were too defined.

Table 1: Environmental datasets used in this study and their sources

Variable	Selection Criteria	Source/Method
Aspect	Important in understanding the dominant type of habitat/microclimate. Identify the quantity of sun potentially received, relates to temperature (GIS Geography 2022)	Taken from the elevation layer (QLD Department of Resources (Queensland Government 2021))
Distance to Water	Frogs are aquatic/semi aquatic animals, require water to live and breed (NSW Government 2020)	Derived from land cover layer (Esri 2019)
Elevation	Consistently mentioned in literature (Puschendorf et al. 2011; Puschendorf et al. 2013; Hoskin & Puschendorf 2014)	QLD Department of Resources (Queensland Government 2021)
Land Cover	Important in understanding the suitable habitat (Pulsford et al. 2018)	ESRI (Esri 2019)
Land Use	Knowledge on how frogs use and live in the environment is limited (Pulsford et al. 2018)	QLD Department of Agriculture and Fisheries
Slope	Important in understanding the most suitable type of habitat/microhabitat. Determines the direction of water flow (GIS Geography 2022)	Taken from the elevation layer of QLD Department of Resources (Queensland Government 2021)

The climate data was taken from the WorldClim (www.worldclim.org/data/bioclim.html) website in which the historical, 10 second climate data was used. Nineteen (19) variables were downloaded and then compared to determine their correlation. Using the Pearson correlation coefficient (r), six variables were found to be not highly correlated ($r < 0.8$) and were chosen. The climate variables that were used in the species distribution modelling are listed below:

- Bio1 – Annual Mean Temperature
- Bio2 – Mean Diurnal Range
- Bio3 – Isothermality
- Bio4 – Temperature Seasonality
- Bio 8 – Mean Temperature of the Wettest Quarter
- Bio12 – Annual Precipitation

3.4 Data Pre-processing, Analysis and Validation

3.4.1 SDM Modelling

The bioregion dataset was brought into ArcGIS from which the study area was clipped to ensure that the area of the Wet Tropics only was shown and used. This clipped dataset was projected into a suitable projection system (MGA Zone 55) and then converted into a raster (grid) map layer with a cell size of 25m by 25m.

The frog sightings datasets were similarly clipped to the study area, projected to the same coordinate system, changed to the same cell size and then rarefied to relieve sampling bias. This rarefication was achieved using the rarefication tool within the SDM Toolbox (Brown 2014). No individual records were excluded. The data was cleaned to ensure that any duplicates were removed. The sightings for each genera were then combined to produce a single text file for that genera which was then exported ready for use in MaxEnt software. The two species in each genera were combined due to a low number of sightings for *Litoria lorica* and *Taudactylus rheophilus* and also because of the similarities within the genera.

Similarly, the environmental datasets were also clipped to the study area and projected to the same coordinate system as the study area. Each file was checked to ensure the same cell size had been incorporated and the same coordinate system was being utilised to ensure high accuracy and validity of the results. These were then rasterised to create an ASCII file for each variable. These ASCII files were combined within a single folder for use in several MaxEnt runs.

The climate data, from the dataset, has undergone the same data processing treatment as the environmental data. Each file was placed into ArcGIS and checked to ensure the same standards as the environmental data were kept. Each file (present as bands within a single .tif) were clipped to the study area and each band was projected into MGA Zone 55 and saved into individual rasters for future use in MaxEnt. From these raster layers, ASC files were created. These were put into a single folder for use in MaxEnt.

The species files along with the environmental and climate data were combined within MaxEnt to determine the current potential habitat for each of the frog species using a variety of models. This was done for both genera to determine the factors which most influence frog habitat. For each model analysed through MaxEnt, an output was given as an asc. file. Each file was then exported back to ArcGIS in order to be converted to a raster for further spatial analysis.

All the climate and environmental variables were tested for collinearity to avoid model overfitting. This was achieved through transformation into float rasters and run through the band correlation statistics in the ArcMap toolbox. This gave a score from 0.1 to 1 and showed how highly correlated the variables are to each other variable. Where a variable was highly correlated to another variable, variables pairs were created and analysed for the relevance to the study. The one that was more beneficial to the study was chosen. Variables were classed as correlated if the score was above 0.8 and this includes inversely correlated variables. The correlation of the variables is shown in Tables 2 and 3 below.

Table 2: The Correlation Statistics of the Climate Variables

	Bio1	**Bio2**	**Bio3**	**Bio4**	**Bio8**	**Bio12**
Bio1	1	0.13	0.29	0.26	0.5	0.11
Bio2	0.13	1	0.25	0.23	0.65	0.48
Bio3	0.29	0.25	1	0.35	0.35	0.67
Bio4	0.26	0.23	0.35	1	0.15	0.44
Bio8	0.5	0.65	0.35	0.15	1	0.48
Bio12	0.11	0.48	0.67	0.44	0.48	1

Bio1 (Annual Mean Temperature); Bio2 (Mean Diurnal Temperature Range); Bio3 (Isothermality); Bio4 (Temperature Seasonality); Bio8 (Mean Temperature of the Wettest Quarter) and Bio12 (Annual Precipitation)

None of the variables are correlated above 0.8 with only two above 0.5. This shows that all the variables have a low correlation to each other and are viable variables to be used in this study.

Table 3: The Correlation Statistics of the Environmental Variables

	Aspect	**Distance to Water**	**Elevation**	**Land Cover**	**Land Use**	**Slope**
Aspect	1	0.32	0.21	0.16	0.00	0.18
Distance to Water	0.32	1	0.29	0.22	0.03	0.25
Elevation	0.21	0.29	1	0.09	0.03	0.21
Land cover	0.16	0.22	0.09	1	0.03	0.35
Land Use	0.00	0.03	0.03	0.28	1	0.05
Slope	0.18	0.25	0.21	0.35	0.05	1

The collinearity tests for the environmental variables show that each variable has a low correlation, with the highest score being 0.35. This means that the environmental variables are less correlated than the climatic variables.

3.4.2 Data Analysis

After the completion of MaxEnt based species distribution modelling, the files were converted back into raster files in order to reclassify the data. This was achieved through the reclassify tool in the ArcGIS toolbox. This reclassification was implemented to categorise the suitability of frog habitat into easy-to-label classes and to locate the areas of higher suitability. Equal intervals were used to create four equal classes, allowing for clean, even results that can be easily separated. This was to ensure the criteria for each class remained the same throughout each mode to facilitate model comparisons. Four classes were used and the data sorted into these classes based on the suitability scores. These scores are derived from the data and are between 0 and 1 with 1 being higher suitability. Class 1 was scores between 0 and 0.25, class 2 was 0.26 to 0.5, class 3 was 0.51 to 0.75 and class 4 was 0.76 to 1. This showed the amount of suitable habitat classes as quarters, in which labels were categorised as “not suitable”, “low suitability”, “moderate suitability” and “high suitability”. This class division was decided upon to give uniform results and to ensure the highest suitability results are more prominently shown while also showing areas of not suitable habitat. The results were then used to calculate the percentage for each class and the corresponding number of hectares per class. The MaxEnt results also gave the relative contribution percentage of variables to the modelling. This showed the percentage that each variable contributed to the model. This allows an understanding of which variables are important to which species.

3.4.3 Model Validation

The results obtained during the MaxEnt modelling in this study were validated using the Area Under the Curve (AUC) statistic of the Receiver Operating Characteristic (ROC) (Hajian-Tilaki 2013). The models were run through MaxEnt using the default "cloglog" format for improved optimisation over the logistic output format and gives an output within the limits of 0 and 1 (Phillips et al. 2017). It also assumes one individual per cell and has the highest probability of assuming correct suitable distribution. For each model 30% of the records were used as training samples. These training samples were used as background points on which to test the data within MaxEnt. The cross-validation tool was also used as part of the modelling.

The results of the AUC can be described as a percentage. The number given as the result were between 0 and 1. The closer the number to 1, the higher the percentage and the better the result (Phillips & Dudik 2008). Anything under 0.5 is below half and should be considered ineffective, as it means the model is using random predictions. Results over 5 are considered good and anything over 7.5 is excellent. If a model comes under 0.5 then a rethink of the modelling is required, for example, the inclusion of more input data or variables (Phillips & Dudik 2008).

CHAPTER 4: CURRENT SPECIES DISTRIBUTION OF *LITORIA* AND *TAUDACTYLUS* FROGS IN THE WET TROPICS

4.1 Introduction

Knowing the spatial distribution of a plant or animal is knowing one of the most basic and fundamental considerations of an animal (Shimada et al. 2021). The spatial distribution of a species is defined as the extent of their distribution across a landscape, whether it be a country, continent or the planet (WTMA 2019). This includes the understanding of the biotic and abiotic factors that influence this distribution and allows for research to be undertaken to understand other aspects of a species life and knowledge into how they interact with and affect their environment (Shimada et al. 2021).

Currently, the spatial distribution of frogs has many knowledge gaps (Cogger 2014) with many species across Australia being understudied and some known from less than five specimens. One particular species found in Central Australia is known from only one dead specimen found by chance (Clulow & Swan 2018).

Frog declines affect 32 frog species out of the 40 that are classed as threatened by the IUCN with 28 of these (70%) being associated with upland areas (Alford & Rowley 2007). 41 (23%) of the species not classed as threatened have restricted ranges. Globally, the average per country for the number of threatened frog species is 10% yet Australia currently sits at 15% (Alford & Rowley 2007).

Spatial distribution uses mapped GPS locations of verified species sightings. Over time a pattern is formed with the sightings showing areas where the species is found, as well as where the species has not been found. The more sightings that are compiled, the more accurate the distribution mapping and a more concise picture is formed. For *Litoria lorica, Litoria nyakalensis, Taudactylus acutirostris* and *Taudactylus rheophilus* the current distributions are currently unknown. Historical sightings from the 1980's and 1990's give an idea of the type of habitat in which each species thrives yet there is still little known regarding some fundamental spatial aspects of these frogs.

The aim of this chapter is to map and analyse the spatial distribution of four critically endangered frog species endemic to Far North Queensland in order to clarify their conservation status and understand potential threats to their distribution.

4.2 Methods

SDMs are a technique that has been around for many years, having first been introduced by Andrew Murray in his 1866 book, '*The Geographical Distribution of Mammals*' and followed by AFW Schimper in 1898 with his book '*Plant Geography on a Physical Basis*', where he used environmental conditions to determine the extent of plants. Following this, it became more common to use environmental factors to determine geographic range. It was not until 1981 that the first modern, computer based SDM was created. Since this time, technology has become more sophisticated, allowing for more accurate modelling. The number of SDM's being conducted each year is steadily rising (Melo-Merino et al. 2020) allowing more insights into suitable habitat for various species.

Species distribution modelling is also known as ecological niche modelling, habitat modelling and predictive habitat distribution. They use complex algorithms to determine the optimal environmental and climatic conditions for a species based on previous sightings. They are reliant on knowledge of the niche of the species. Three types of SDM's are recognised: correlative, process based and mechanistic. A correlative approach is one in which the ecological requirements of a species are estimated through known geographic distributions and a set of variables. A process based approach is one in which the dispersal is analysed through biotic and dispersive factors such as dispersal capabilities and biotic interactions (Melo-Merino et al. 2020) while a mechanistic approach uses detailed physiological information and the first principle of biophysics. This study uses a correlative approach to model the current and future distribution.

The study area and SDM techniques used in this chapter follow those methods described in Chapter 3 (Methodology). MaxEnt was used to determine the suitable habitat of each frog species through the use of eight different models. This approach was employed across two different shared socioeconomic pathways to analyse how different variables change the amount and degree of suitable habitat. These different models are presented below:

Model 1: *Litoria* species and environmental data only

Model 2: *Taudactylus* species and environmental data only

Model 3: *Litoria* species with climate data only

Model 4: *Taudactylus* species with climate data only

Model 5: *Litoria* species with climate and environmental data – elevation included

Model 6: *Taudactylus* species with environmental and climate data – elevation included

Model 7: *Litoria* species with environmental and climate data – elevation excluded

Model 8: *Taudactylus* species with environmental and climate data – elevation excluded

The "environmental data only" comprises the following variables:

- Slope
- Aspect
- Elevation
- Land Use
- Land Cover
- Distance to Water

The "climate data only" includes:

- Bio1 – Annual Mean Temperature
- Bio2 – Mean Diurnal Temperature Range
- Bio3 – Isothermality
- Bio4 – Temperature Seasonality
- Bio8 – Mean Temperature of the Wettest Quarter
- Bio12 – Annual Precipitation

"Environmental and climate data" is comprised of all the above variables.

Elevation was excluded from models 7 and 8 in order to determine the effect elevation has on the distribution of these species. This was due to *Litoria lorica* being rediscovered lower than it was previously thought to inhabit, questioning the previous ideas of elevation restraints for these species.

4.3 Results

4.3.1 Habitat Suitability

Model 1 for *Litoria lorica* (environmental data only) gave widely distributed suitable habitat across the study area resulting in 16.7% or 297,996 hectares of the Wet Tropics being classed as high suitability and a further 31.2% (555,423 hectares) being classed as moderate suitability with only 15.7% (280,756 hectares) classed as not suitable. As shown in Table 4, for *Litoria nyakalensis* there were less favourable results with only 6.8% (121, 373 hectares) of the Wet Tropics being classed as highly suitable habitat (121,373 hectares) and 12.3% (218,715 hectares) classed as moderately suitable. Approximately 60% (1,062,229 hectares) was classed as not suitable for this species.

Table 4: Model 1: Litoria species (environmental data only): Current Climate SDM Results

Habitat Suitability:	Hectares:	% of Habitat:
Litoria lorica		
Not Suitable	280,752	15.7
Low Suitability	652,005	36.6
Moderate Suitability	555,423	31.2
High Suitability	297,996	16.7
Litoria nyakalensis		
Not Suitable	1,062,229	59.7
Low Suitability	383,823	21.5
Moderate Suitability	218,715	12.3
High Suitability	121,373	6.8

The environmental data only resulted in a similar disparity for the two *Taudactylus* species, as shown in Table 5, with only 5.3% (95,336 hectares) of the Wet Tropics seen as high suitability and 9.9% (175,728 hectares) as moderately suitable for *Taudactylus acutirostris*. This is in stark contrast to *Taudactylus rheophilus* which is shown to have only 0.07% (1,274 hectares) being classed as highly suitable in contradiction to the more respectable 58.1% (1,032,731 hectares) being classed as moderately suitable. There were 62.3% (1,118,858 hectares) for *Taudactylus acutirostris* that were classed as not suitable. Despite having little highly suitable habitat, *Taudactylus rheophilus* has little of the Wet

Tropics as not suitable with only 2.1% (37,676 hectares) classed as not suitable. Therefore, the vast majority of the Wet Tropics is either moderate suitability or high suitability.

Table 5: Model 2: Taudactylus species (environmental data only): Current Climate SDM Results

Habitat Suitability:	Hectares	% of Habitat
Taudactylus acutirostris		
Not Suitable	1,118,858	62.3
Low Suitability	396,253	22.3
Moderate Suitability	175,728	9.9
High Suitability	95,336	5.3
Taudactylus rheophilus		
Not Suitable	37,676	2.1
Low Suitability	714,495	40.2
Moderate suitability	1,032,731	58.1
High Suitability	1,274	0.07

Table 6 shows the results from Model 3 (climate data only) for the two *Litoria* species which produced more uniform results than model 1 with *Litoria lorica* having 14.4% (256,293 hectares) of the Wet Tropics regarded as highly suitable habitat and 15.34%(272,791 hectares) considered as moderately suitable while *Litoria nyakalensis* is shown to have 11.4% (201,758 hectares) of its potential habitat thought to be highly suitable and 20.4% regarded as moderately suitable habitat. *Litoria lorica* shows a range that becomes more suitable as the latitude rises with 256,293 hectares (14.4%) considered highly suitable compared to the 861,802 hectares (48.5%) considered not suitable. This is a contraction from the model 1 results which showed 297,996 (16.7%) as highly suitable and only 280,756 (15.7%) as not suitable habitat. *Litoria nyakalensis*, however, shows a range increase with the amount of suitable habitat growing from 6.8% (121,373 hectares) to 11.4% (201,758 hectares).

Table 6: Model 3: Litoria species (climate data only): Current Climate SDM Results

Habitat Suitability:	Hectares	% of Habitat
Litoria lorica		
Not Suitable	861,802	48.5
Low Suitability	394,833	22.2
Moderate Suitability	272,791	15.3
High Suitability	256,293	14.4
Litoria nyakalensis		
Not Suitable	746,917	42
Low Suitability	480,739	27
Moderately Suitability	356,306	20.4
High Suitability	201,758	11.4

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The climate only model for the two *Taudactylus* species (model 4) shows that only 5% (89,646 hectares) of the habitat is high suitability for *Taudactylus acutirostris* while 6.2% (110,547 hectares) is moderate suitability. As shown by Table 7, *Taudactylus rheophilus* has 14.9% (265,339 hectares) of the habitat regarded as high suitability and 25.2% (444,870 hectares) considered moderate suitability. The climate only model for the *Taudactylus* species shows a contraction of the range of *Taudactylus acutirostris* and an increase in the potential range of *Taudactylus rheophilus*. For *Taudactylus acutirostris* the high suitability habitat has shrunk from 5.3% to 5%. A contraction of 5,690 hectares.

Table 7: Model 4: Taudactylus species (climate data only): Current Climate SDM Results

Habitat Suitability:	Hectares	% of Habitat
Taudactylus acutirostris		
Not Suitable	1,302,590	73.3
Low Suitability	282,974	15.9
Moderate Suitability	110,547	6.2
High Suitability	89,646	5
Taudactylus rheophilus		
Not Suitable	344,838	19.4
Low Suitability	730,573	41.1
Moderate Suitability	444,970	25.2
High Suitability	265,339	14.9

As shown in Table 8, in the results for the two *Litoria* species in model 5 (environmental and climate data – elevation included) there was little favourable habitat for either *Litoria lorica* or *Litoria nyakalensis*. *Litoria lorica* had 9.7% (172,238 hectares) marked as moderately suitable and 9.2% (164,302 hectares) declared to have high suitability by the model. *Litoria* *nyakalensis* had just 5.3% (93,278 hectares) of the habitat regarded as high suitability and 8.2% (145,141 hectares) thought to be moderate suitability. The habitat is skewed towards unfavourable habitat with 1,131,488 hectares (63.6%) regarded as not suitable for *Litoria lorica* and 1,278,107 hectares (71.9%) for *Litoria nyakalensis*. Therefore, 36% (646,791 hectares) of the habitat is suitable in some form for *Litoria lorica* and 28% (500,172 hectares) for *Litoria nyakalensis*. 59.7% of the study area is considered not suitable for *Litoria nyakalensis.*

Table 8: Model 5: Litoria species (environmental and climate data – elevation included): Current Climate SDM Results

Habitat Suitability:	Hectares	% of Habitat
Litoria lorica		
Not Suitable	1,131,488	63.6
Low Suitability	310,250	17.5
Moderate Suitability	172,238	9.7
High Suitability	164,302	9.2
Litoria nyakalensis		
Not Suitable	1,278,107	71.9
Low Suitability	261,752	14.7
Moderate Suitability	145,141	8.2
High Suitability	93,278	5.3

Table 9 indicates the amount of highly suitable habitat for *Taudactylus acutirostris* equalled 82,840 hectares. This is 4.7% of the habitat. The habitat classed as moderate suitability was 212,633 hectares or 11.9% of the Wet Tropics. In contrast *Taudactylus rheophilus* had 252,481 hectares (14.2%) of the habitat considered highly suitable and 249, 244 hectares (14%) classed as suitable. The results for model 6 show that for *Taudactylus acutirostris* there was a 14.2% difference between Model 4 and Model 6.

Table 9: Model 6: Taudactylus species (environment and climate data – elevation included): Current Climate SDM Results

Habitat Suitability:	Hectares	% of Habitat
Taudactylus acutirostris		
Not Suitable	1,383,064	77.8
Low Suitability	212,633	11.9
Moderate Suitability	99,740	5.6
High Suitability	82,840	4.7
Taudactylus rheophilus		
Not Suitable	670,196	37.7
Low Suitability	606,356	34.1
Moderate Suitability	249,244	14
High Suitability	252,481	14.2

When elevation is excluded from the model, 1,130,718 hectares (63.6%) of the habitat is considered not suitable for *Litoria lorica* while 163,806 (9.2%) is considered highly suitable (Table 10). The percentage of the habitat that is considered unsuitable remains the same. This is not true of the number of hectares with small differences in the amount of habitat considered highly suitable. A difference of 5,770 hectares that is no longer considered suitable with the removal of the elevation variable. For *Litoria nyakalensis* the amount of high suitability habitat was 5.2%. Also the same amount as model 5. The habitat that is not suitable, decreased to 71.8% which is a marginal decrease. *Litoria lorica's* suitable habitat is 9.8% of the Wet Tropics and the amount of high suitability habitat is 9.2%. *Litoria nyakalensis* did not fare as well as *Litoria lorica* with only 8.2% of the habitat regarded as moderate suitability and 5.2% regarded as high suitability for the species.

Table 10: Model 7: Litoria species (environment and climate data – elevation excluded): Current Climate SDM Results

Habitat Suitability:	Hectares	% of Habitat
Litoria lorica		
Not Suitable	1,130,718	63.6
Low Suitability	310,213	17.4
Moderate Suitability	173,541	9.8
High Suitability	163,806	9.2
Litoria nyakalensis		
Not Suitable	1,276,618	71.8
Low Suitability	262,800	14.8
Moderate Suitability	145,681	8.2
High Suitability	93,179	5.2

Model 8 is comparable to Model 7 but uses the two *Taudactylus* species rather than the *Litoria* species. This model resulted in rather dismal results, as shown in Table 11, for *Taudactylus acutirostris* with 2% of the habitat regarded as moderate suitability and only 6% classed as high suitability. *Taudactylus rheophilus* fared better with 15.9% of the habitat thought to have moderate suitability and 12.1% high suitability. 1,376,858 hectares, or 78%, is not suitable for *Taudactylus acutirostris* compared with 662,291 hectares (37.5%) for *Taudactylus rheophilus*. This is only a minimal change for *Taudactylus acutirostris* and indicates that elevation only has a marginal impact on the suitability of habitat for *Taudactylus acutirostris*. The removal of elevation has caused a decline in the amount of suitable habitat for *Taudactylus rheophilus* as the habitat has declined from 252,481 hectares (14.2%) to 215,935 hectares (12.1%). A drop of 36,546 hectares or 2.1% of the habitat.

Table 11: Model 8: Taudactylus species (environment and climate data – elevation excluded): Current Climate SDM Results

Habitat Suitability:	Hectares	% Habitat
Taudactylus acutirostris		
Not Suitable	1,376,848	78
Low Suitability	215,638	12.5
Moderate Suitability	103,406	2
High Suitability	82,386	6
Taudactylus rheophilus		
Not Suitable	662,291	37.2
Low Suitability	617,469	34.7
Moderate Suitability	282,585	15.9
High Suitability	215,935	12.1

4.3.2 Habitat Requirements

The variables that were seen as most important within the model are presented in Table 12. For *Litoria lorica* the most important variable was slope with land cover and land use being second and third. This is different to *Litoria nyakalensis* whose most important variables went from elevation to distance to water to land use. This difference in variables shows that these two species are influenced by different conditions. The variables of *Litoria nyakalensis* were also more equally divided with elevation contributing to 28.1% of the model, distance to water contributed 25.2% and land use 23.5% while *Litoria lorica* had slope contribute 47.1% to the modelling, land cover 32.9% and land use 19.9%.

Table 12: Model 1: Litoria species with Environmental Data Only: Variable Results

Variable:	Percent Contribution:
Litoria lorica	
Slope	47.1
Land Cover	32.9
Land Use	19.9
Litoria nyakalensis	
Elevation	28.1
Distance to Water	25.2
Land Use	23.5
Aspect	13.2

The most important variables for model 2 were elevation, land use and distance to water for *Taudactylus acutirostris*, as shown in Table 13; while land use, land cover and aspect were most important for *Taudactylus rheophilus*. This shows that land use is an important variable for the two *Taudactylus* species used in this study and that both *Taudactylus* species require common environmental variables in their chosen habitats. It can also be seen that the model for *Taudactylus acutirostris* had a 68.4% contribution by elevation and a 19.6% modelling contribution from land use but *Taudactylus rheophilus* had an 81.6% contribution from land use and a 16.9% contribution from land cover.

Table 13: Model 2: Taudactylus Species with Environmental Data Only: Variable Results

Variable:	Percent Contribution:
Taudactylus acutirostris	
Elevation	68.4
Land Use	19.6
Distance to Water	6
Land Cover	2.6
Taudactylus rheophilus	
Land Use	81.6
Land Cover	16.9
Aspect	1.6

Table 14 shows that the climate variables are more aligned for the two *Litoria* species compared to the environmental variables. For *Litoria nyakalensis* mean temperature of the wettest quarter was the most important variable followed by temperature seasonality and annual mean temperature. For *Litoria lorica,* temperature seasonality was the most influential variable, taking 98.6% of the contribution to modelling with isothermality taking 1.2% and annual precipitation taking 0.1%. *Litoria nyakalensis* was more distributed in its variables with the most important variable -- mean temperature of the wettest quarter only contributing 48.2% of the modelling. This is followed by temperature seasonality at 35.8% and annual mean temperature at 9.6%.

Table 14: Model 3: Litoria Species with Climate Data Only: Variable Results

Variable	Percent Contribution
Litoria lorica	
Temperature Seasonality	98.6
Isothermality	1.2
Annual Precipitation	0.1
Litoria nyakalensis	
Mean Temperature of the Wettest Quarter	48.2
Temperature Seasonality	35.8
Annual Mean Temperature	9.6
Isothermality	5
Annual Precipitation	1.1

Table 15 shows that the climatic variables of the Wet Tropics are more suited to *Taudactylus rheophilus* than it is to *Taudactylus acutirostris*. The variables show that mean temperature of the wettest quarter, temperature seasonality and annual mean temperature are the most important climate variables for *Taudatylus acutirostris* and similarly *Taudactylus rheophilus* relies on temperature seasonality, mean temperature of the wettest quarter and annual mean temperature for a favourable habitat. This shows that the climate requirements of these two species are similar. For *Taudactylus acutirostris* there was a 39.2% modelling contribution by mean temperature of the wettest quarter, with temperature seasonality contributing 27.1% and annual mean temperature 24.4% while temperature seasonality contributed 95.7% to the modelling for *Taudactylus rheophilus*.

Table 15: Model 4: Taudactylus Species with Climate Data Only: Variable Results

Variable:	Percent Contribution
Taudactylus acutirostris	
Mean Temperature of the Wettest Quarter	39.2
Temperature Seasonality	27.1
Annual Mean Temperature	24.4
Mean Diurnal Temperature Range	7.4
Isothermality	1
Taudactylus rheophilus	
Temperature Seasonality	95.7
Mean Temperature of the Wettest Quarter	2.5
Annual Mean Temperature	1.8

The most important variables in this model were temperature seasonality, slope and land cover for *Litoria lorica* and temperature seasonality, elevation and land use for *Litoria nyakalensis,* as seen in Table 16. For this model the clear result was the importance of temperature seasonality for the selection of suitable habitat. Temperature seasonality contributed 67.4% to the modelling with slope contributing 16.6% and land cover contributing 9.1% for *Litoria lorica*. For *Litoria nyakalensis* temperature seasonality contributed 19.5%, elevation contributed 19.4% and land use 19.1%.

Table 16: Model 5: Litoria species with Environment and Climate Data – Elevation Included: Variable Results

Variable	Percent Contribution
Litoria lorica	
Temperature Seasonality	67.4
Slope	16.6
Land Cover	9.1
Land Use	5.6
Annual Precipitation	1
Litoria nyakalensis	
Temperature Seasonality	19.5
Elevation	19.4
Land Use	19.1
Distance to water	17.5
Aspect	10.2

Model 6 consisted of climate and environmental data with elevation included for the *Taudactylus* species, as can be seen in Table 17. The variables that were most important to *Taudactylus acutirostris* in this model were elevation, temperature seasonality and annual mean temperature. For *Taudactylus rheophilus* the variables were temperature seasonality, land use and land cover with elevation coming in 4th. Land use came in 5th for *Taudactylus acutirostris*. The variables contributed 30.4% (elevation), 21.6% (temperature seasonality) and 14% (annual mean temperature) for *Taudactylus acutirostris* while for *Taudactylus rheophilus* the variables contributed 59.9% (temperature seasonality), 31.5% (land cover) and 7.4% (land use).

Table 17: Model 6: Taudactylus species with Environment and Climate Data – Elevation Included: Variable Results

Variable	Percent Contribution
Taudactylus acutirostris	
Elevation	30.4
Temperature Seasonality	21.6
Annual mean temperature	14
Mean Temperature of the Wettest Quarter	10
Land Use	8.7
Taudactylus rheophilus	
Temperature Seasonality	59.9
Land Use	31.5
Land Cover	7.4
Elevation	0.8
Aspect	0.4

Model 7 has the same variables as Model 5 but with the exclusion of elevation to determine the overall importance that elevation has on these species. In this model *Litoria lorica* was most reliant on temperature seasonality, slope and land cover with the most important variable, temperature seasonality, contributing 67.4% to the modelling. This was followed by slope at 16.6% and land cover at 9.1%. The most important variables for *Litoria nyakalensis* were land use, distance to water and temperature seasonality. These contributed 18.5%, 17.8% and 16.1%. Table 18 below, gives an overview of this.

Table 18: Model 7: Litoria species with Environment and Climate Data – Elevation Excluded: Variable Results

Variable	Percent Contribution
Litoria lorica	
Temperature Seasonality	67.4
Slope	16.6
Land Cover	9.1
Land Use	5.6
Precipitation	1
Litoria nyakalensis	
Land Use	18.5
Distance to water	17.8
Temperature Seasonality	16.1
Mean Temperature of the Wettest Quarter	14.9
Isothermality	9.6

Table 19 indicates the variables with the most weight for *Taudactylus acutirostris* were mean temperature of the wettest quarter, temperature seasonality and annual mean temperature. For *Taudactylus rheophilus* they were temperature seasonality, land use and land cover. These were weighted as mean temperature of the wettest quarter with 33.2%, temperature seasonality with 24.1% and annual mean temperature with 21.8% for *Taudactylus acutirostris* and temperature seasonality with 60.4%, land use with 31.8% and land cover with 7.5%.

Table 19: Model 8: Taudactylus species with Environment and Climate Data – Elevation Excluded: Variable Results

Variable	Percent Contribution
Taudactylus acutirostris	
Mean Temperature of the Wettest Quarter	33.2
Temperature Seasonality	24.1
Annual Mean Temperature	21.8
Land Use	8.3
Mean Diurnal Temperature Range	4
Taudactylus rheophilus	
Temperature Seasonality	60.4
Land Use	31.8
Land Cover	7.5
Aspect	0.4

4.3.3 Model Outputs

As shown in figure 11, the majority of the Wet Tropics is seen as suitable for *Litoria lorica* based on environment only variables with the most suitable habitat concentrated above latitude -16.75°. This is shown as the dark green habitat within Figure 11. For *Litoria nyakalensis* (Figure 12) the suitable habitat is concentrated on the west of the study area with the highly suitable habitat concentrated to the west of longitude 146° and small patches scattered throughout the rest of the Wet Tropics.

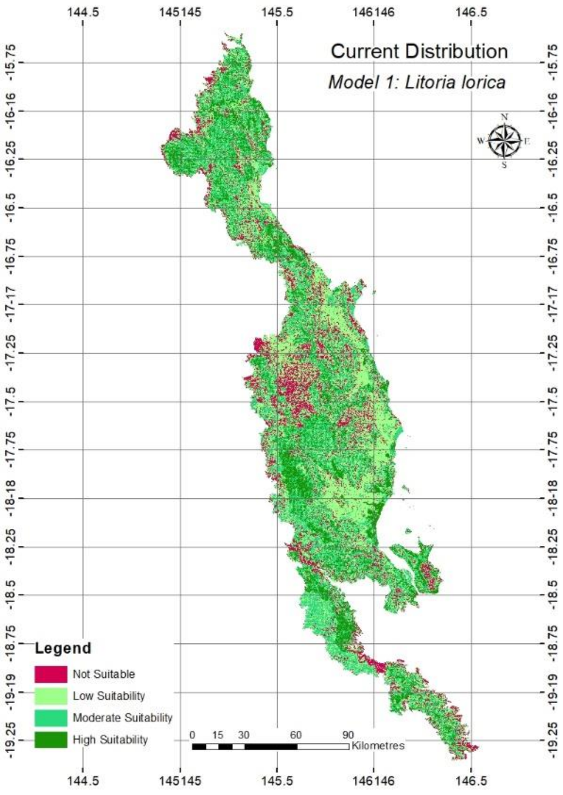


Figure 11: The model 1 output for Litoria lorica

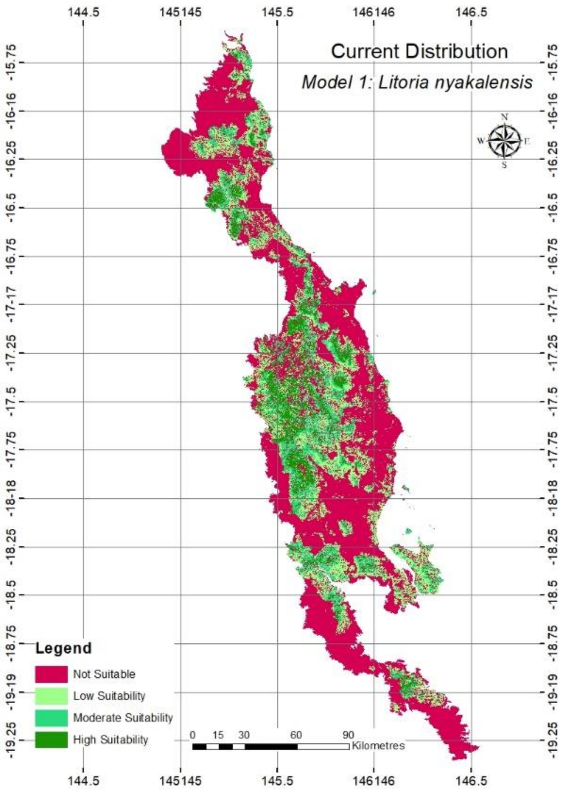


Figure 12: The model 1 output for Litoria nyakalensis

As shown in figure 13, there are highly suitable patches on the westernmost edge, between longitudes 145.25° and 145.5° of the study area and there is no suitable habitat past longitude 145° for *Taudactylus acutirostris* aside from one isolated patch at latitude -19°. Figure 14 shows that for *Taudactylus rheophilus* all but 2.1% (Table 5) of the area is some form of suitable therefore the output appears in the different shades of green representing suitability across the entire area with highly suitable habitat shown to be central of the study area. The moderately suitable extends from this towards the coast in each direction.

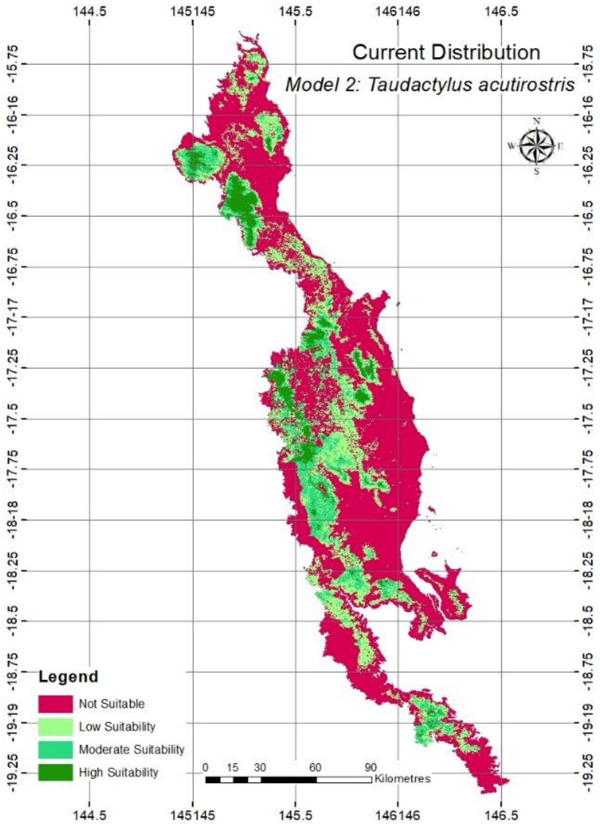


Figure 13: The model 2 output for Taudactylus acutirostris

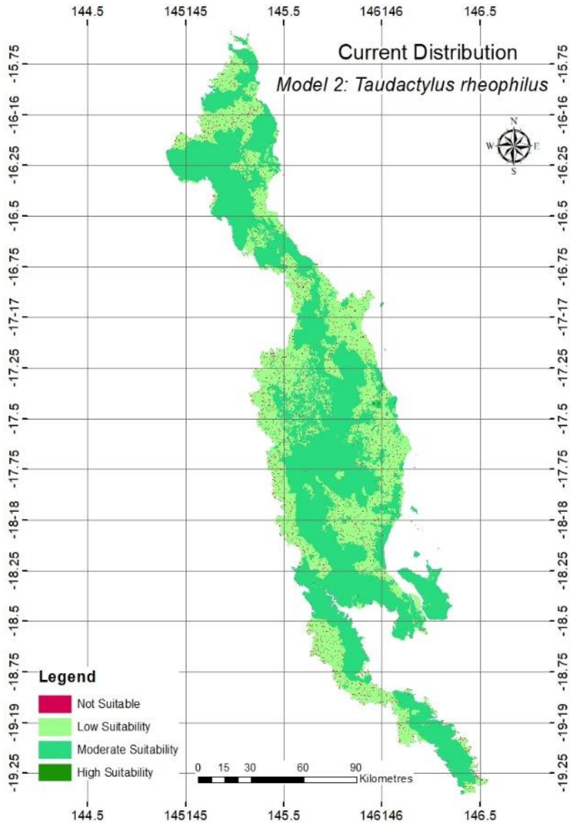


Figure 14: The model 2 output for Taudactylus rheophilus

The environmental variables show different areas of suitable habitat for *Litoria lorica*. In this model, the most suitable habitat is above latitude -16º with a strip extending down the coast as seen in Figure 15. The moderately suitable habitat is not seen below latitude -17.25º and the low suitability habitat below latitude -18º. Figure 16 identifies the most suitable habitat for *Litoria nyakalensis* as two large patches. An increase from model 1. The first patch begins at latitude -16.2º and ends at -16.3º while the second extends from -17.2º to -17.75º. There is no suitable habitat below -18.25º.

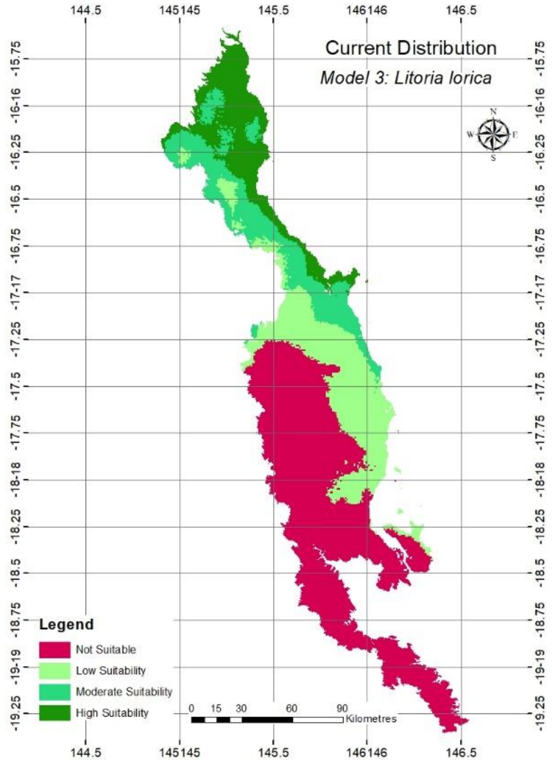


Figure 15: The model 3 output for Litoria lorica

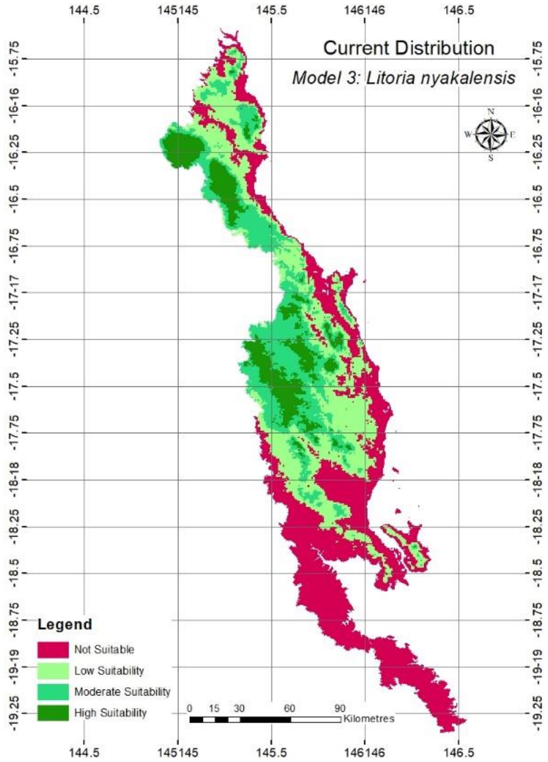


Figure 16: The model 3 output for Litoria nyakalensis

The amount of habitat is reduced in model 4 for both species compared to model 2. For *Taudactylus acutirostris* the largest patch of highly suitable habitat is to the northwest between latitudes -16.5° and -16.7°, as shown in Figure 17. For *Taudactylus rheophilus* it is to the north with the most suitable habitat above latitude -16.4° and the moderately suitable habitat above -17.25° as described in Figure 18.

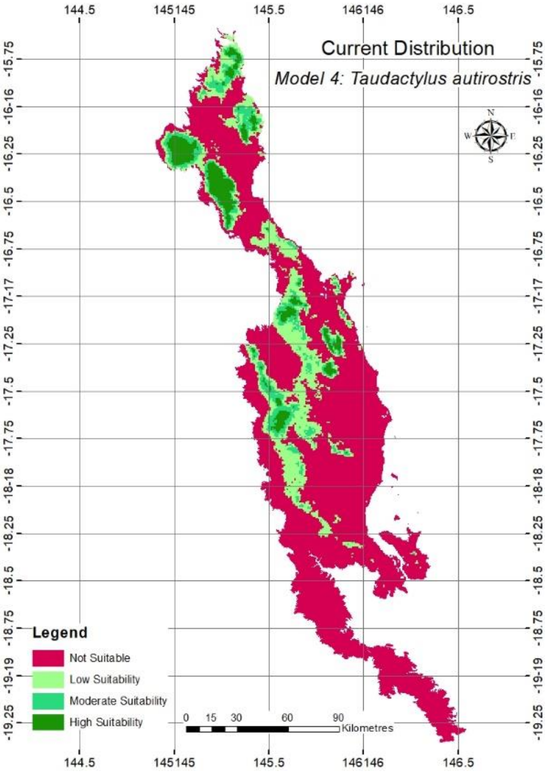


Figure 17: The model 4 output for Taudactylus acutirostris

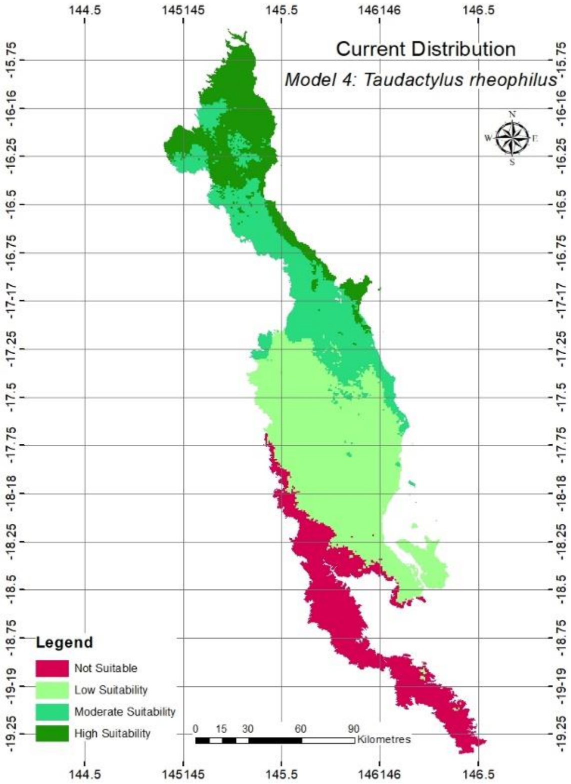


Figure 18: The model 4 output for Taudactylus rheophilus

Figures 19 and 20 show a reduction in the optimal habitat from model 5 for both species although the overall habitat appears the same. The highly suitable habitat for *Litoria lorica* is now only above –17.17°. For *Litoria nyakalensis* the majority of the habitat is still on the western boundary and is now in smaller patches between latitudes -18° and -16.2° with a visible increase in the amount of habitat not considered suitable.

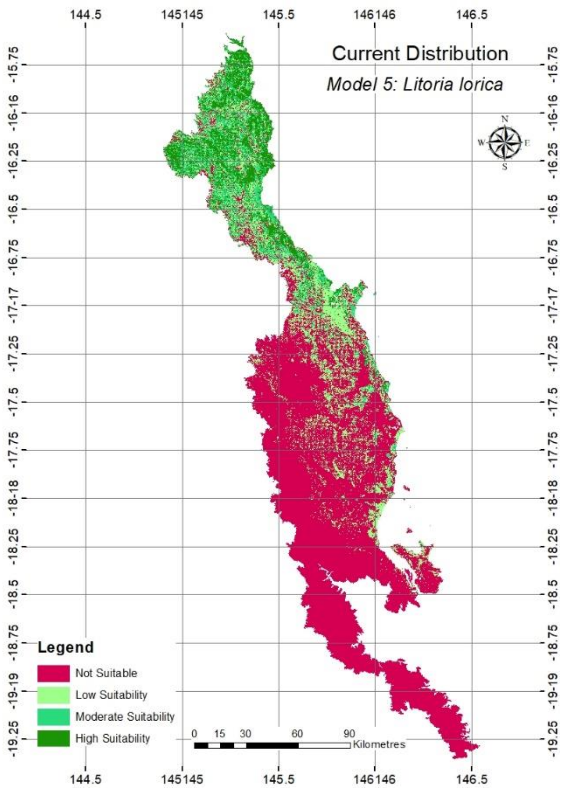


Figure 19: The model 5 output for Litoria lorica

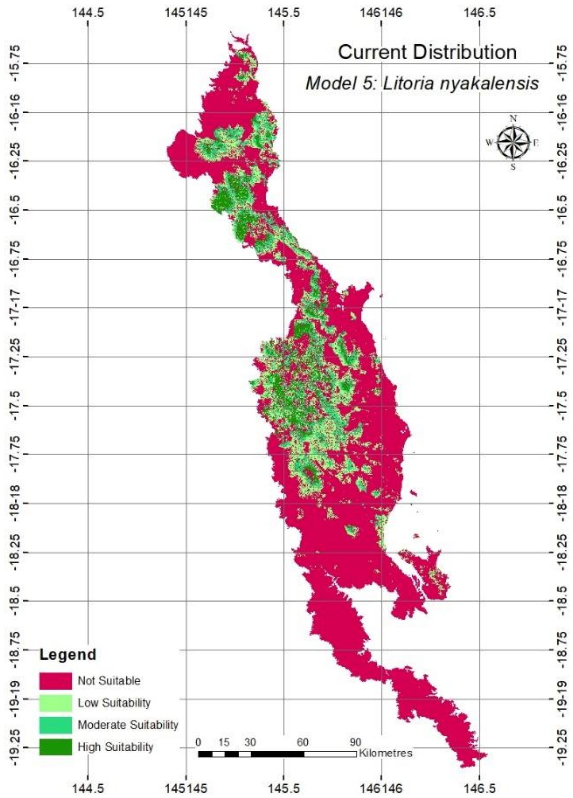
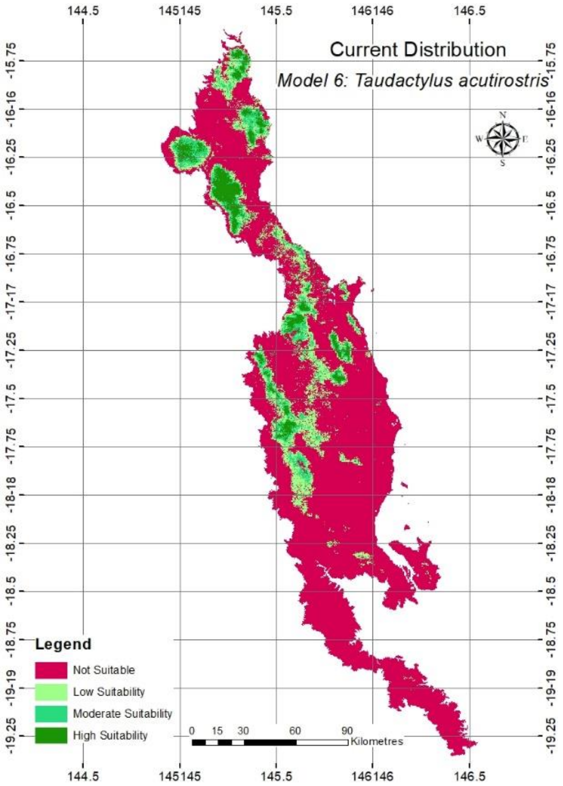


Figure 20: The model 5 output for Litoria nyakalensis

Taudactylus acutirostris (Figure 21) shows there is a patch of highly suitable habitat at latitude -16.5° latitude on the western edge of the study area. For *Taudactylus rheophilus* (Figure 22) there is still a large area from -17.2° latitude and above that is highly suitable. This includes large areas of highly suitable and moderately suitable habitat. Under -17.2° latitude there is still moderate and low suitability habitat in the centre of Wet Tropics which continues down to latitude -18.5°.



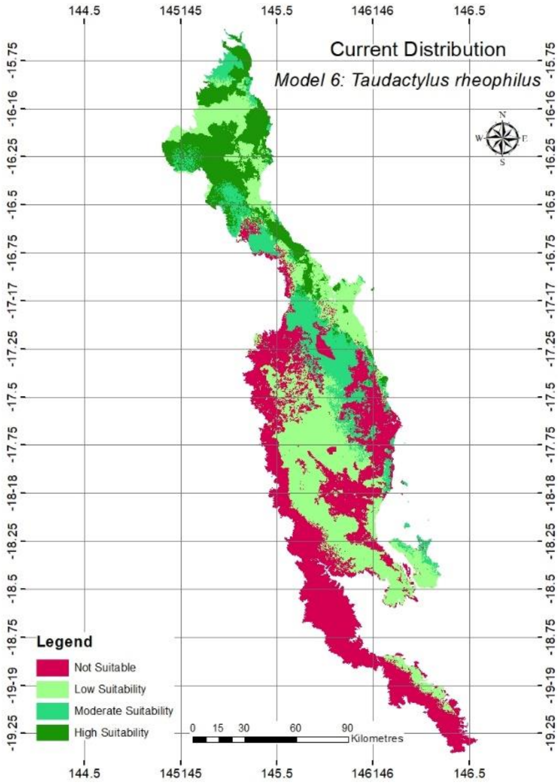
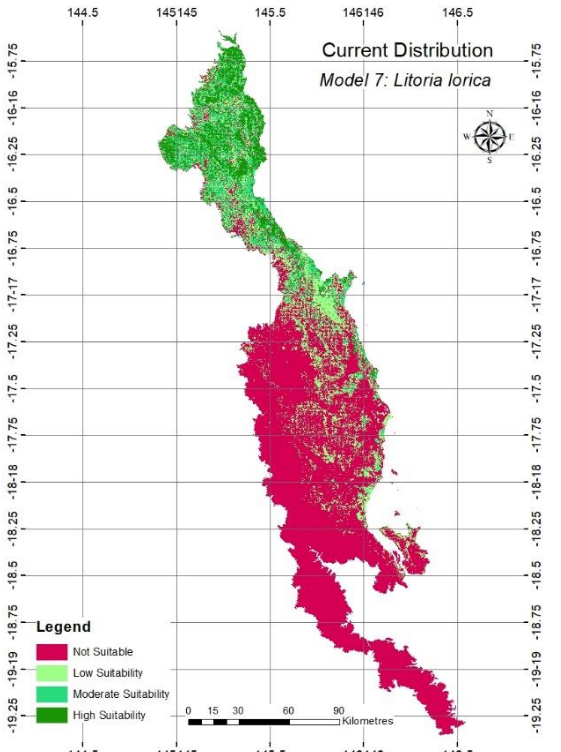


Figure 21: The model 6 output for Taudactylus acutirostris *Figure 22: The model 6 output for Taudactylus rheophilus*

Figure 23 shows the continued decrease in suitable habitat for *Litoria lorica.* It is now only found above -17° latitude while the suitable habitat for *Litoria nyakalensis* (Figure 24) is restricted to small patches on the westernmost side of the Wet Tropics between latitudes -16.25° and -17.5°.



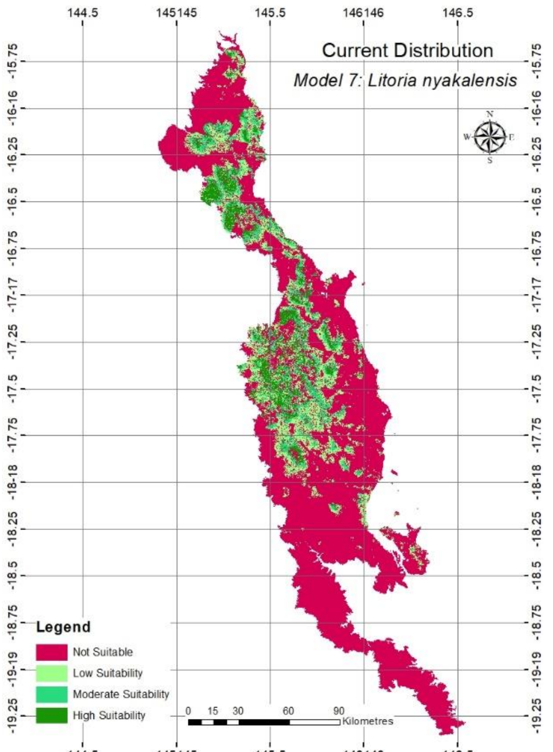


Figure 23: The model 7 output for Litoria lorica *Figure 24: The model 7 output for Litoria nyakalensis*

Model 8 for *Taudactylus acutirostris* (Figure 25) indicates there are small patches of high suitability habitat between latitudes -16.25° and -16.75° with moderate suitability habitat running along the western side of the wet tropics. Figure 26 for *Taudactylus rheophilus* shows there are fragmented patches between latitudes -15.5° and -17.2° with moderate and low suitability patches continuing across the wet tropics.

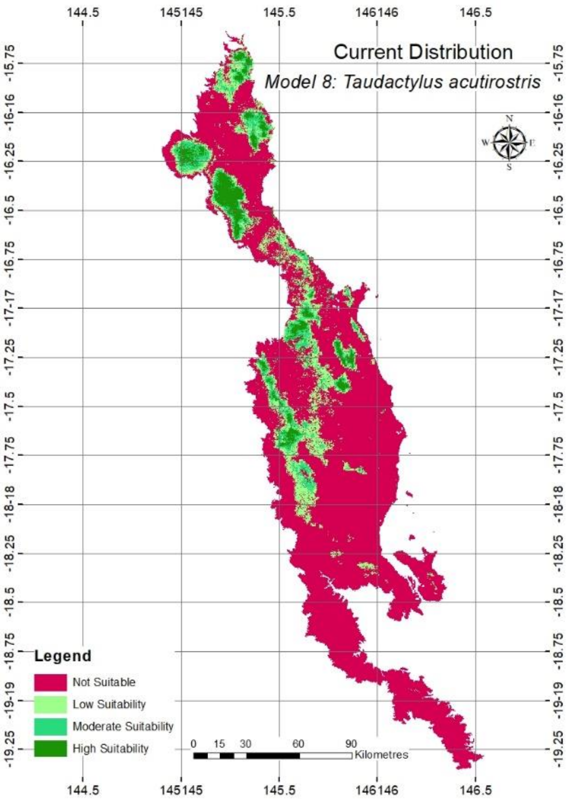


Figure 25: Model 8 output for Taudactylus acutirostris

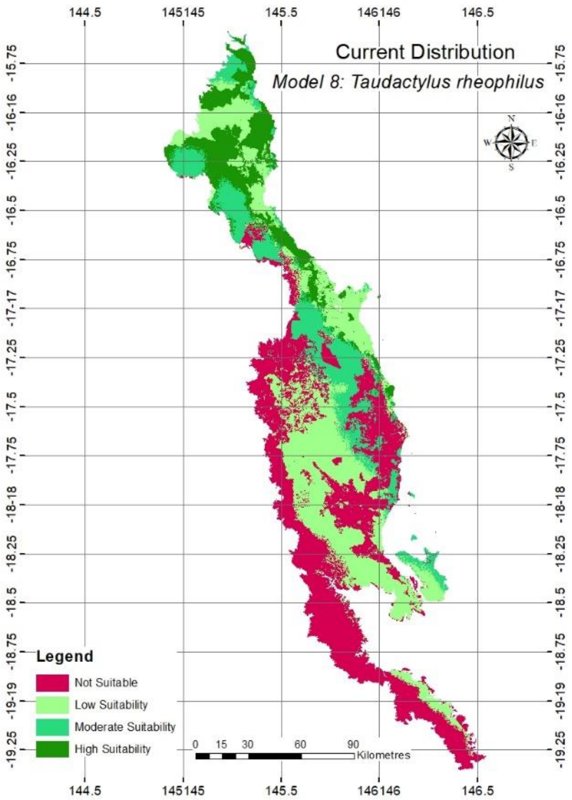


Figure 26: Model 8 output for Taudactylus rheophilus

4.3.4 Model Validation

The area under the curve is used to determine the probability of the model being correct. The higher the number in the area under the ROC curve (AUC), the more likely it is that the model is correct (Mandrekar 2010). A score over 0.8 is excellent, over 0.6 is good, but under 0.5 is fail and the model has no discrimination (Mandrekar 2010). In this study the lowest score was 0.45 for *Litoria lorica*. This shows the model in question (model 3 – environmental variables only) was underfitted due to *Litoria lorica* being more reliant on climatic variables. The low number of sightings for *Litoria lorica* possibly also contributed. As shown in figure 27, the next three lowest scores were all over 0.6 and all belonged to *Litoria nyakalensis*. The average AUC score was 0.76, giving a high overall score. The figure below shows an overview of the AUC scores in these models. The species with consistently the highest score was *Taudactylus acutirostris* which peaked at 0.9 in model 4.The AUC curve results indicate high accuracy within the models demonstrating the areas specified to be viable habitat are in fact, viable habitat.

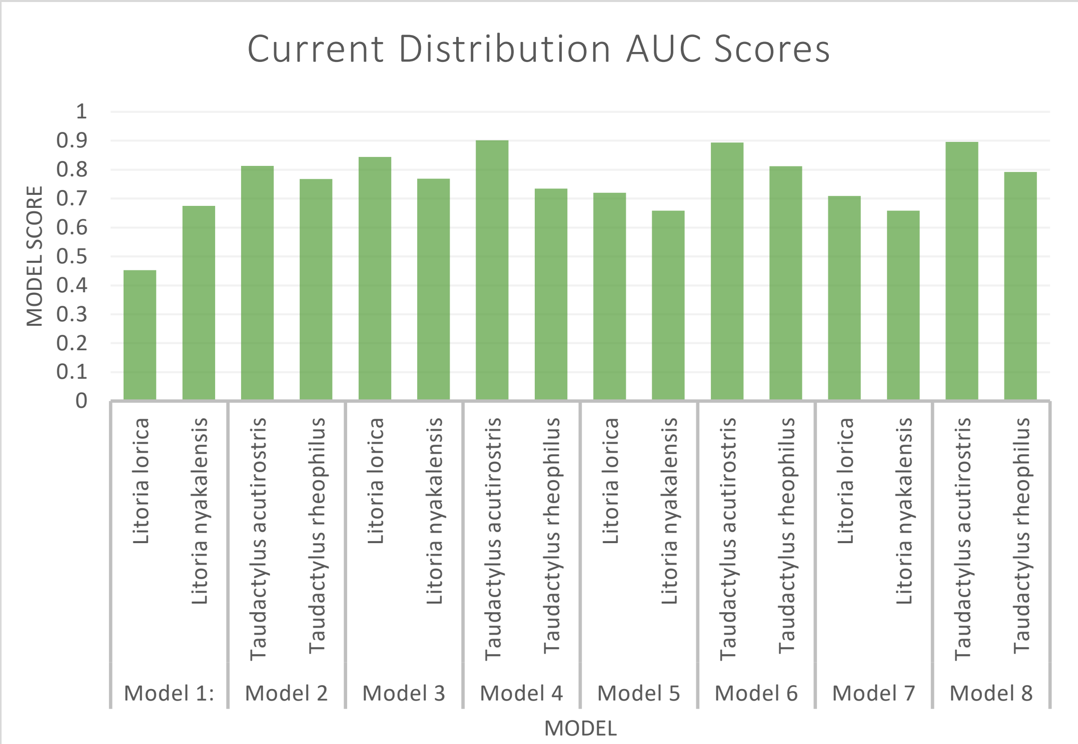


Figure 27: The AUC modelling scores for the current distribution

4.4 Discussion

4.4.1 Habitat Requirements

The results show that while there are similarities between the habitats of these species there are marked differences in the variables that make these habitats important. While inhabiting the same area, each species has different environmental and climatic requirements which mean that different areas of the Wet Tropics are more suitable than other areas.

It is clear from the modelling that these species are not closely related in terms of habitat requirements. *Litoria lorica* is less aligned to the environmental variables than *Litoria nyakalensis* with the most important environmental variable being temperature seasonality. A comparison of the results shows more highly suitable habitat available in model 3 compared to model 1. There are 41,703 hectares (2.4%) more classed as highly suitable in model 3. This shows that climatic variables are more important to *Litoria lorica* in habitat selection than environmental variables. Extended analysis of the results in ArcGIS shows the most important land cover type is trees with 61% of the land cover type containing highly suitable habitat for *Litoria lorica*. This corroborates with the literature such as Puschendorf et al. (2011) and Puschendorf et al. (2013). A further 16% of the highly suitable habitat is on scrub/shrub land and 7% is both on land classed as water and built-up areas. From the land use layer, the most important land types for *Litoria lorica* are seen to be nature conservation with 24.8% and grazing native vegetation with 12.4% as these are the most likely to be housing these frogs. Other marginal potential land types are managed resource protection, other minimal uses, services and marsh/wetlands. The environmental factors that are important to *Litoria lorica* are slope, land cover and land use while for the climatic variables it is temperature seasonality followed by annual precipitation. The habitat of *Litoria lorica* is shown to not be determined by elevation with low lying areas shown as highly suitable habitat. The results indicate that the lower elevations (those under 450m) are more suitable to *Litoria lorica* in today's climate with 48.7% of the highly suitable habitat being found at lower elevations (150m). This is a contradiction to the literature as it was thought this species only lives between 640m and 1000m (Puschendorf et al. 2011). The amount of suitable habitat is seen to decrease with elevation and while there is still highly suitable habitat at the highest elevations (over 1500m), it equals only 1% of the study area.

It is the opposite for *Litoria nyakalensis*, which favours the cooler, higher areas of the western boundaries of the Wet Tropics with elevation being the most important environmental factor. Temperature seasonality appears to be the most important climatic variable, ranking above elevation in model 5, followed by isothermality. The optimal temperatures for *Litoria nyakalensis* are between 18°C and 24°C with a diurnal temperature range between 7°C and 9°C. The isothermality appears to be suitable when between 49 and 57, showing that *Litoria nyakalensis* prefers even temperatures for each month of the year. The temperature seasonality shows little is suitable under 22.5% and nothing is suitable over 32.5%, affirming that *Litoria nyakalensis* prefers only a small amount of variability in the seasons. From the analysis it appears that the most promising elevations are those between 600m and 1050m. When these are optimal, land use and distance to water source are the most important deciding factors. The data provided by the Department of Climate Change; Energy; Environment and Water (2022d) considers elevations between 380 and 1020m to be the most suitable.

The exclusion of elevation in model 7 allows for the variables of land use and distance to water to become more prominent. Annual precipitation shows that *Litoria nyakalensis* is tolerant of precipitation between 2000 and 5000mL per year. When comparing these variables using the combine tool it can be seen that the grass land cover is where the majority of the highly suitable habitat is found. For the grass land cover 20.3% of the habitat ranked a high suitability and a further 22.1% ranked as moderate suitability. The land cover types of scrub/shrub, water and trees were also seen to have just under 10% of the areas highly suitable habitat and between 15% and 17% of the moderately suitability. The land use types that were seen to be most important were nature conservation, irrigated cropping and other minimal uses. Nature conservation had 27.6% of the area identified as high suitability and 16.2% regarded as moderate suitability while the irrigated cropping had 13.3% as high suitability and 7.4% considered moderate suitability. 10.3% and 9.3% were the scores for the other minimal uses. Little work appears to have been done on this species in the past preventing the comparison between this data and historical data.

The results for *Taudactylus acutirostris* and *Taudactylus rheophilus* show a distinct difference in habitat requirements similar to the disparities between *Litoria lorica* and *Litoria nyakalensis*. *Taudactylus acutirostris* appears to be more reliant on the climatic variables with annual mean temperature, mean temperature of the wettest quarter and temperature seasonality consistently the top 3 variables.

With the *Taudactylus* species, elevation appears to be more important for *Taudactylus acutirostris* and according to the models is the most important variable, appearing as number one in all models except model 8 (environmental and climate data – elevation excluded). When elevation is excluded the most important environmental variable becomes land use. The results for *Taudactylus acutirostris* shows the most important land cover types are trees, grass and built-up areas with trees taking 25.1% of the high suitability habitat, scrub/shrub taking 18.1% and built-up areas taking 18.6%. These numbers were still significantly high for the moderate suitability habitat where trees took 24.7%, scrub/shrub took 15.2% and built up areas took 18.5%. With the land use types, it was clearly nature conservation, residential and farm infrastructure and services where it is most likely frogs of *Taudactylus acutirostris* will be found with 18.5%, 15.6% and 16.1%. For *Taudactylus acutirostris* the results show that the midrange elevations (between 300m and 1050m) are more suitable where the temperatures are lower. The optimal temperatures are temperatures over 18°C with less suitable results over 27°C. In the wettest quarter (mean temperature of the wettest quarter) it is shown that the optimal temperature should be between 23°C and 27°C. Precipitation is preferred between 2000mL and 5000mL and seasonality is from 22.5% to 32.5%, further demonstrating the optimal temperatures for this species.

The available literature on this species indicates a strong association with permanent streams (Clarke 2006) where it has been found in and around large, fast flowing streams but the modelling shows a less strong relationship as residential and farm infrastructure and services were major land use types. Seepage areas were identified by Clarke (2006) as potential habitat and this agrees with the results of the modelling. The modelling also matches the results of Richards et al. (1993) who state this frog is only found above 300m elevation.

Environmental variables seem to be more important in determining habitat for *Taudactylus rheophilus* over *Taudactylus acutirostris*, with more environmental variables showing in the model results. These include land use, land cover and aspect. When looking at the results it is clear that grass is the most favourable land cover type for *Taudactylus rheophilus* with 54.1% of the high suitability habitat falling within this land cover type. The moderate suitability habitat follows suit with 35.2%. The next best land cover type is trees at 11.7% for high suitability and scrub/shrub with 10.8% of the highly suitable habitat. Interestingly, bare ground accounted for 6.3% of the high suitability habitat. The results for the preferred land use types show that nature conservation is clearly the most important land use for *Taudactylus rheophilus* with 46.9% of the high suitability habitat occurring on this land use. This is followed by managed resource protection at 8.1% and other minimal uses at 5.4%. Hoskin and Hero (2008) have presented data to support this with *Taudactylus rheophilus* being found in small streams and associated seepage areas. The modelling suggests that the lower elevations are more suitable for *Taudactylus rheophilus* with elevations under 600m being the most suitable. A contradiction of the work of Marshall (1998) where this species was found in high altitude streams. *Taudactylus rheophilus* prefers warmer temperatures, with the optimal range between 18°C and 24°C with little variation in the diurnal temperate range (between 6°C and 8°C). This species prefers precipitation levels to remain between 2000mL and 4000mL per year with the mean temperature of the wettest quarter clearly preferred to be between 25°C and 27°C with 39.42% of the modelling showing in favour of this temperature. The range is shown to be within acceptable limits if between 21°C and 27°C but is not happy with temperatures under 19°C.

4.5.2 Changes to Climate Stability

The climate of the Wet Tropics has been stable for millennia and therefore the species that live in the Wet Tropics are not well equipped to deal with changes to this stability. This change could be in the form of more extreme seasons or increased annual temperatures.

In this study the biggest threat is shown to be climate change for all four frog species as temperature seasonality is the most significant variable from the modelling. This shows that a change in the temperature seasonality will affect the stability of the climate and this will have significant effect on these frogs. This is particularly true for *Taudactylus acutirostris* and *Litoria nyakalensis* which favour the cooler temperatures of elevations over 600m. Even *Taudactylus rheophilus*, who prefers temperatures in the higher range, has shown it does not like a change in the stability of the climate. If the temperature rises, the frogs will be forced to move upwards in order to remain in those conditions most favourable, despite there being only so far they can go, particularly for *Litoria nyakalensis*, who already inhabits higher elevations.

Chytridiomycosis is also potentially a factor for those species who lives in areas of greater density cover with less solar radiation (Reside et al. 2019b), in particular *Litoria lorica* and *Taudactylus acutirostris* who have shown they prefer areas covered by trees rather than the grass preferred by *Litoria nyakalensis* and *Taudactylus rheophilus*. Testing needs to be done on these species in order to determine susceptibility, mortality and recovery rates.

For those species to whom grass is a favourable land cover type there is less of a risk of succumbing to this virus as direct sunlight can alleviate its affects (Reside et al. 2019a).

Large scale land clearing is a significant factor (NSW Government 2022) and can never be ruled out despite the harshness of parts of the Wet Tropics and its status as a protected area. The clearing of important habitat will leave frogs that have an already reduced distribution, at best, on the edge of extinction. Small scale clearing, as for building of a few houses, could possibly benefit *Taudactylus acutirostris* which has been shown to have the potential to live around residential areas.

4.4.3 Significance of the Results

The analysis of the results shows that many of the preconceptions of habitat requirements for these species have been false and assumptions on the more suitable areas have been in the wrong places. These species are not reliant on mountaintops for survival and potentially are more suited to life at lower elevations such as appears the case for *Litoria lorica* and *Taudactylus rheophilus* where higher elevations were considered to be an essential part of the habitat requirements. This study has shown the potential areas of habitat for these four species are varied and in different parts of the Wet Tropics. The results show that there are different parts of the habitat available that appear to not have been involved in previous manual searches.

Litoria lorica is more constrained by climatic variables while *Litoria nyakalensis* is limited to higher elevations. *Litoria lorica* and *Taudactylus acutirostris* prefer tree cover while *Litoria nyakalensis* and *Taudactylus rheophilus* prefer grass habitats.

While all four frogs have most of their highly suitable habitat on land classed under nature conservation, *Litoria nyakalensis* can also be found in areas of cropping while *Litoria lorica* and *Taudactylus acutirostris* can be found in built up areas.

Taudactylus acutirostris and *Taudactylus rheophilus* were thought to have similar habitat requirements (Clarke 2006) but this has been contradicted with these frogs relying on different land types, different land covers and different environmental and climatic variables. *Taudactylus acutirostris* and *Taudactylus rheophilus* have different requirements and should not be compared to other *Taudactylus* species, including each other.

CHAPTER 5: PROJECTED IMPACT OF CLIMATE CHANGE ON FROG SPECIES

5.1 Introduction

Climate change is a significant issue for species across the planet. It is the extended change in the average state of the climate, outside what is considered the normal climatic parameters for that area and the creation of more extreme weather (WTMA 2019). The change is expected to worsen over time due to humanities insistence on using climate wrecking fossil fuels (BOM & CSIRO 2020) and even a 1°C temperature rise will have significant adverse effects on the species of the Wet Tropics (WTMA 2019). The IPCC (Intergovernmental Panel on Climate Change) has recently released its latest reports and these reports details four potential scenarios of carbon emissions. These scenarios act as future guides to the effects of partially mitigated and unmitigated climate change. These Shared Socioeconomic Pathways (SSP) (Parry et al. 2007b) as they are known, detail the impacts of climate change if we were to follow those scenarios. The environmental effects will be rising sea levels, changed phenological cycles, altered areas of suitable habitat, increased extreme weather and natural disasters, increased solar radiation and altered water cycles (Parry et al. 2007a).

In Australia the current climate has warmed by approximately 1.4°C since 1910 which has led to an increase in heat events, a reduction in the amount of dry season rainfall and an increase in streamflow across northern Australia (Parry et al. 2007b). This has occurred with a correlating reduction in streamflow across southern Australia, an increase in fire intensity and fire seasonality, a decrease in the number of cyclones. Oceans have also acidified and become more exposed to heatwaves and sea levels have risen, causing inundation to coastal islands and communities (BOM & CSIRO 2020). These effects will continue and worsen the longer climate change is not mitigated.

Frogs are known to be particularly sensitive to changes in the environment. A significant change in the climate is likely to see a frogs range severely contracted. There are three factors which lead to frogs being more susceptible to climate change: frogs are ectotherms and any change in the temperature can limit their activity; they require constant access to water in order to avoid drying out and thirdly; frogs require free water in order to breed (Lemckert & Penman 2012). Frogs require moist, cool conditions to thrive, not something likely to be seen in the future unless climate change is mitigated.

Studies from the Northern hemisphere have shown that climate change is already affecting frogs through the altered the phenology of frogs breeding cycles, changes to breeding sites, reduced moisture content and an increased impact of disease (Lemckert & Penman 2012). These studies are yet to have been done on the frogs of Australia. Those species of frog that have reduced or narrow ranges are more susceptible to the effects of climate change and are more likely to become extinct (Lemckert & Penman 2012).

In the current distribution chapter (Chapter 4) the variables that were used in this study were analysed for their importance in determining the current distribution of frog species. This chapter focuses on the change in these variables' importance in order to ascertain their necessities in surviving climate change.

5.2 Methods

The future scenario bioclimatic variables were downloaded from the BioClim website (Fick & Hijmans 2021). ACCESS CM2 variables for SSP126 for 2021 - 2040 and 2061 – 2080 were downloaded for use in this study. This study used the IPCC's Shared Socio-Economic Pathways to determine the climatic effects of climate change. SSP126 variables were used. This is the most optimistic variable and assumes some emissions reductions and eventual plateauing but still results in a 2°C rise by 2100. SSP585 (the least optimistic option) was considered and rejected due to a lack of suitable habitat by 2040. These variables were used to determine the future habitat of frogs under the most extreme climate change scenario. The environmental variables were the same as those used in the current distribution models in chapter 4. These are aspect, slope, elevation, land use, land cover and distance to water.

The general procedures for data processing were similar to those implemented in Chapter 4 of this study. The variables were clipped to the study area of the Wet Tropics using the boundaries taken from the Queensland bioregions dataset, as was used in the current distribution models. The clips were then converted to the projected coordinate system of MGA GDA 2020 and the cell size was also converted to 25m x 25m in order for each file to align.

The models are as laid out in Chapter 4 with Models 3 to 8 repeated here. As this chapter is focused on the change in climatic variables, models 1 and 2 will not be repeated here. Models 3 and 4 will be climate data only while models 5 to 8 will involve both climatic and environmental data. Refer to the method section of Chapter 4 for more details.

5.3 Future Climate Modelling Results

5.3.1 Habitat Suitability

The results for model 3 (climate variables only) for the future projections show that there 1,009,015 hectares (56.5%) of the Wet Tropics that is suitable in some form for *Litoria lorica* in 2040, while 260,587 hectares, or 14.7%, have high suitability (Table 20). This is in contrast to the 769,262 hectares, or 43.5%, that is not suitable. For *Litoria nyakalensis* there are 939,874 hectares of suitable habitat, equalling 57.5% in 2040. Of this, 10.9% is highly suitable with 194,212 hectares. *Litoria nyakalensis* has 758,806 hectares, or 42% of the habitat, which is not suitable. This shows that *Litoria lorica* is more suited to the climate of 2040 than is *Litoria nyakalensis*.

When this is compared to the suitability data for 2080, it is clear that there is less suitable habitat for *Litoria lorica*. While having 260,587 hectares of highly suitable habitat in 2040, there is now 231,135 hectares of highly suitable habitat for *Litoria lorica*. This is a decrease of 426,173 hectares overall. *Litoria nyakalensis* sees an increase of the high suitability habitat from 194,212 hectares to 202,725 hectares, a rise of 0.5% of the habitat and 8,513 hectares. The amount of habitat classed as moderately suitable also increased from 338,845 hectares (19.1%) to 366,003 hectares (20.6%). The amount of habitat considered not suitable decreased by 20,154 hectares (1.1%).

Table 20: Model 3: Future Projection SDM Results for Litoria Species: Climate Variables Only

Habitat Suitability:	*Hectares*	*% Habitat*	*Hectares*	*% Habitat*
	2040		2080	
Litoria lorica				
Not Suitable	769,262	43.5%	845,846	47.6%
Low Suitability	476,235	26.8%	403,834	22.7%
Moderate Suitability	272,193	15.3%	304,905	17.2%
High Suitability	260,587	14.7%	231,135	13%
Litoria nyakalensis				
Not Suitable	758,806	42.5%	738,652	41.5%
Low Suitability	497,85	28%	478,340	26.9%
Moderate Suitability	338,845	19.1%	366,003	20.6%
High Suitability	194,212	10.9%	202,725	11.4%

As shown in Table 21, the results for the future climate modelling shows that little changed from 2040 to 2080 for either *Taudactylus acutirostris* or *Taudactylus rheophilus*. The not suitable and low suitability classes increased by 8,345 hectares or 0.2% (not suitable) and 1,818 (low suitability) *Taudactylus acutirostris* while the available high suitability habitat decreased by 0.1% or 2,079 hectares. The not suitable habitat for *Taudactylus rheophilus* increased by 1.8% or 32,920 hectares while each other class decreased. The low suitability habitat decreased by 2.3% or 23,942 hectares. Both the habitat considered to be moderate suitability and the habitat thought to be high suitability decreased by 0.2% or 4,421 hectares.

Table 21: Model 4: Future Projection SDM Results for Taudactylus Species: Climate Variables Only

Habitat Suitability:	Hectares	% of Habitat	Hectares	% of Habitat
	2040		2080	
Taudactylus acutirostris				
Not Suitable	1,310,071	73.7%	1,308,252	73.5%
Low Suitability	273,183	15.4%	281,528	15.8%
Moderate Suitability	107,981	6%	103,535	5.8%
High Suitability	94,485	5.31%	92,405	5.2%
Taudactylus rheophilus				
Not Suitable	333,587	18.8%	366,507	20.6%
Low Suitability	729,349	41%	705,406	39.7%
Moderate Suitability	423,683	23.8%	419,261	23.6%
High Suitability	299,101	16.8%	294,545	16.6%

The future climate results shown in Table 22 for the 2040 modelling show that there is more habitat that is unsuitable than suitable for both *Litoria lorica and Litoria nyakalensis* when the climate and environmental variables are combined. *Litoria nyakalensis* appears to fare marginally better in 2040 with low suitability covering 16.4% (291,006 hectares) of the Wet Tropics and moderate suitability covering 9.4% (167,767 hectares) although high suitability is only 5.2% (91,787 hectares) of the study area. In comparison, *Litoria lorica* has 14.1% (250,606 hectares) regarded as low suitability and 8.3% (147,557 hectares) considered to have moderate suitability and another 7.2% (128,641 hectares) that is thought to be high suitability. In modelling for 2080 where the amount of suitable habitat decreases significantly.

For *Litoria nyakalensis* the amount of habitat with high suitability decreases by 50% from 14.7% in model 3 to 5.2% (91,787 hectares) in model 5 with the amount of habitat considered unsuitable increasing to 69% (1,227,718 hectares). The number of hectares with high suitability also decreases to almost half from model 3 where there were 194,212 to 91,787 hectares in model 5. A change of 102,424 hectares. For *Litoria lorica* the same decreases are evident. The amount of habitat regarded as highly suitable is reduced from 14.7% in model 3 to 7.2% in model 5 with the amount of unsuitable habitat going from 43.5% to 70.3%.

In the 2080 modelling it can be seen that there is little suitable habitat remaining for either *Litoria lorica* or *Litoria nyakalensis*. *Litoria lorica* has 94.9% of the habitat regarded as not suitable with the remaining 4.6% classed as low suitability. This means no area of the Wet Tropics will be suitable for *Litoria lorica* by 2080. The result is the same for *Litoria nyakalensis* with 99.8% of the habitat considered not suitable by 2080 and only 0.13 hectares thought to have high suitability.

Table 22: Model 5: Future Projection SDM Results for Litoria Species: Environmental and Climatic Variables – Elevation Included

Habitat Suitability:	Hectares	% Habitat	Hectares	% Habitat
	2040		2080	
Litoria lorica				
Not Suitable	1,250,223	70.3%	1,687,472	94.9%
Low Suitability	250,606	14.1%	81,468	4.6%
Moderate Suitability	147,557	8.3%	9,337	0.5%
High Suitability	128,641	7.2%	0	0%
Litoria nyakalensis				
Not Suitable	1,227,718	69%	1,777,819	99.8%
Low Suitability	291,006	16.4%	453	0%
Moderate Suitability	167,767	9.4%	5.6	0%
High Suitability	91,787	5.2%	0.1	0%

Model 6 (environmental and climate variables – elevation included) shows that there is little suitable habitat for *Taudactylus acutirostris* with 77.4%, or 1,376,295.57 hectares that is not considered suitable. This is described in Table 23, where 5.6% is considered moderately suitable and only 4.6% is thought to be highly suitable. *Taudactylus rheophilus* has 29.7% that is not suitable with 18.2% that is moderately suitable and 17.1% that is high suitability. Model 6 shows a contraction in the range of both *Taudactylus* species. In this model there is 77.4% of the study area declared not suitable compared to 73.3% in model 4 for *Taudactylus acutirostris*. This is in comparison to the 28.7% of the habitat not suitable for *Taudactylus rheophilus*, a rise from the 16.8% in model 4. This shows that the amount of suitable habitat increased by 66,223.01 hectares for *Taudactylus acutirostris* and decreased for *Taudactylus rheophilus* by 194,228.87 hectares. The habitat thought to be highly suitable for *Taudactylus acutirostris* in model 6 is 4.6%, a decrease of 34,156.5 from the 5.3% in model 4. There was 17.1% of the Wet Tropics that is highly suitable for *Taudactylus rheophilus*, an increase of 5,052 hectares.

The results for model 6 (environment and climate variables – elevation excluded) in 2080 show that there is a distinct decrease in the amount of suitable habitat. As Table 22 shows, there is now very little habitat considered suitable for *Taudactylus acutirostris* with 0.01% considered to have high suitability. This combined with 0.11% moderately suitable and 1.2% low suitability makes very little overall habitat for this species. The results for

Taudactylus rheophilus show even worse results with only 0.02% considered moderately suitable and only 56 hectares considered to have high suitability (0%). This is the largest decrease with a loss of 304,153 hectares, or 17.1%. Overall, only 47,238.76 hectares is considered suitable habitat with most of this thought to have low suitability. 98.3% of the habitat is considered not suitable.

Table 23: Model 6: Future Projection SDM Results for Taudactylus Species: Environmental and Climatic Variables – Elevation Included

Habitat Suitability:	Hectares	% Habitat	Hectares	% Habitat
	2040		2080	
Taudactylus acutirostris				
Not Suitable	1,376,294	77.4%	1,754,685	98.7%
Low Suitability	220,574	12.4%	21,471	1.2%
Moderate Suitability	99,917	5.6%	1,904	0.1%
High Suitability	81,492	4.6%	240	0.01%
Taudactylus rheophilus				
Not Suitable	527,816	29.7%	1,731,040	97.3%
Low Suitability	623,102	35%	46,764	2.6%
Moderate Suitability	323,206	18.2%	418	0%
High Suitability	304,153	17.1%	56	0%

The results for model 7 (environment and climate variable – elevation excluded) show that there is 70.4% of habitat that is not suitable for *Litoria lorica* with only 7.2% regarded as having high suitability (Table 24). This equates to 128,641 hectares of the Wet Tropics. *Litoria nyakalensis* has 69% of the Wet Tropics regarded as unsuitable which equates to 1,226,840 hectares, similar to the 1,251,473 hectares for *Litoria lorica*. There is 5.2% of the habitat (92,082 hectares) which is highly suitable for *Litoria nyakalensis* and 9.4% (168,167) that is moderately suitable.

In model 7 there is little change from model 5 with the exclusion of elevation. The amount of unsuitable habitat changes from 70.3% to 70.4% for *Litoria lorica* and remains at 69% for *Litoria nyakalensis*. The number of unsuitable hectares for *Litoria lorica* changes from 1,250,223 hectares to 1,251,473 while the hectares for *Litoria nyakalensis* changes from 1,227,718 in model 5 to 1,226,840. This shows that although the percentage remains the same, the area changes by 877 hectares. The percentage of habitat that is highly suitable remains the same for both species from model 5. This is 5.2% for *Litoria nyakalensis* and 7.2% for *Litoria lorica*.

When compared to the 2080 data it can be seen that the habitat decreases further. The results show that 100% of the habitat is unsuitable for *Litoria nyakalensis* in 2080. Only 0.02% is thought to have low suitability and 0.01% to have moderate suitability with 0% of the habitat thought to be highly suitable equating to 0.13 hectares. The results are only slightly better for *Litoria lorica* with 94.9% of the habitat thought to be unsuitable. Almost 5% of the habitat is regarded as having low suitability and no part of the habitat is thought to have high suitability.

Table 24: Model 7: Future Projection SDM Results for Litoria species: Environmental and Climatic Variables – Elevation Excluded

Habitat Suitability:	Hectares	% Habitat	Hectares	% Habitat
	2040		2080	
Litoria lorica				
Not Suitable	1,251,473	70.4%	1,687,472	94.9%
Low Suitability	250,606	14.1%	81,468	4.6%
Moderate Suitability	147,557	8.3%	9,337	0.5%
High Suitability	128,641	7.2%	0	0%
Litoria nyakalensis				
Not Suitable	1,226,840	69%	177,803	100%
Low Suitability	291,19	16.4%	471	0%
Moderate Suitability	168,167	9.4%	4	0%
High Suitability	92,082	5.2%	0	0%

The results for Model 8 (environment and climate variables – elevation included) for *Taudactylus* show that there is a significant amount of habitat that is still suitable for these species in 2040. As seen in Table 25 *Taudactylus acutirostris* has 4.6% of the study area classed as high suitability, 5.5% classed as moderate suitability and 12.3% classed as low suitability. This totals 398,718 hectares with 81,814 of this considered to have high suitability. *Taudactylus rheophilus* only has 29.7% (527,815.82 hectares) classed as not suitable, making the majority of the area suitable in some form. 17.1% of the habitat, 304,153 hectares, is considered highly suitable. Model 8 shows there is 77.6% of the habitat that is not suitable for *Taudactylus acutirostris*, a slight increase from the 77.4% of model 6. There is a change in the number of hectares with 3216 more now suitable. For

Taudactylus rheophilus there is now 29.7% that is not suitable, an increase of 0.5 hectares. *Taudactylus rheophilus* now also has 17.1% that is highly suitable, no change from model 6 although the area has increased by 0.6 hectares. *Taudactylus acutirostris* habitat that is highly suitable has increased by 321.5 hectares.

Less than 1.5% of the habitat is suitable under 2080 conditions with 98.6% regarded as not suitable. This means 24,531 hectares have some form of suitability for *Taudactylus acutirostris*. This is a loss of 374,204 hectares in forty years. *Taudactylus rheophilus* comparatively has 47,237 hectares of potentially suitable habitat, a loss of 1,203,226 hectares. For *Taudactylus rheophilus* 97.3% of the habitat is unsuitable while 2.6% is considered to have low suitability.

Table 25: Model 8: Future Projection SDM Results for Taudactylus Species: Environmental and Climatic Variables – Elevation Excluded

Habitat Suitability:	Hectares	% Habitat	Hectares	% Habitat
	2040		2080	
Taudactylus acutirostris				
Not Suitable	1,379,511	77.6%	1,753,748	98.6%
Low Suitability	218,454	12.3%	22,909	1.3%
Moderate Suitability	98,449	5.5%	1,488	0.1%
High Suitability	81,814	4.6%	132	0%
Taudactylus rheophilus				
Not Suitable	527,815	29.7%	1,731,040	97.3%
Low Suitability	623,102	35%	46,764	2%
Moderate Suitability	323,206	18.2%	417	0%
High Suitability	304,153	17.1%	56	0%

5.3.2 Habitat Requirements

Table 26 shows that for *Litoria lorica* there is only one important variable in this model in both 2040 and 2080. This is temperature seasonality which has 100% of the variable importance. For *Litoria nyakalensis* the most important variables were mean temperature of the wettest quarter, temperature seasonality and isothermality. In 2080, this changed to mean temperature of the wettest quarter, temperature seasonality and annual mean temperature. Mean temperature of the wettest quarter has an importance percentage of 59.6%, while temperature seasonality has importance percentage of 28.1% and isothermality contributed 5.9%. In 2040, the variables for *Litoria nyakalensis* were more evenly spread with mean temperature of the wettest quarter contributing 59.8% to the modelling, temperature seasonality contributing 28.1% and isothermality contributing 5.9%. In 2080, this changed to mean temperature of the wettest quarter contributing to 53.5% of the modelling, temperature seasonality contributing 33.2% and annual mean temperature contributing 9.7%.

Table 26: Model 3: Future Projection Variable Results for Litoria species: Climatic Variables Only

Variable	Percent Contribution	Variable	Percent Contribution
2040		2080	
Litoria lorica		*Litoria lorica*	
Temperature Seasonality	100	Temperature Seasonality	100
Litoria nyakalensis		*Litoria nyakalensis*	
Mean Temperature of the Wettest Quarter	*59.6*	Mean Temperature of the Wettest Quarter	53.5
Temperature Seasonality	28.1	Temperature Seasonality	33.2
Isothermality	*5.9*	Annual Mean Temperature	9.7
Annual Precipitation	3.6	Isothermality	2
Annual Mean Temperature	*2.1*	Annual Precipitation	1.5

Table 27 shows that *Taudactylus acutirostris* has a wider variety of variables than *Taudactylus rheophilus*. The most important variable for *Taudactylus rheophilus* is temperature seasonality which has 97% of the variable importance in 2040. The other 3% comes from mean temperature of the wettest quarter. In 2080 this is reduced to 91.9% with mean temperature of the wettest quarter contributing 8.9%. In 2040 *Taudactylus acutirostris* is most reliant on mean temperature of the wettest quarter with 37.1% importance, followed by annual mean temperature at 30% and temperature seasonality at 23.9%. In 2080 this changed to annual mean temperature with a 32.5% contribution to the modelling, mean temperature of the wettest quarter with a 32.2% contribution to the modelling and mean diurnal temperature range with an 8.3% modelling contribution.

Table 27: Model 4: Future Projection Variable Results for Taudactylus species: Climatic Variables Only

Variable	Percent Contribution	Variable	Percent Contribution
2040		2080	
Taudactylus acutirostris		*Taudactylus acutirostris*	
Mean Temperature of the Wettest Quarter	37.1	Annual Mean Temperature	32.5
Annual Mean Temperature	30	Mean Temperature of the Wettest Quarter	32.2
Temperature Seasonality	23.9	Temperature Seasonality	24.9
Mean Diurnal Temperature Range	6.9	Mean Diurnal Temperature Range	8.3
Annual Precipitation	1.4	Isothermality	1.1
Taudactylus rheophilus		*Taudactylus rheophilus*	
Temperature Seasonality	97	Temperature Seasonality	91.9
Mean Temperature of the Wettest Quarter	3	Mean Temperature of the Wettest Quarter	8.9

The most important variable in this model, as shown in Table 28, for *Litoria lorica* in the 2040 projection was temperature seasonality at 47.9%, followed by land use at 20% and slope at 16.2%. The most important variables for *Litoria nyakalensis* were distance to water at 20.8%, followed by elevation at 17.5% and temperature seasonality. This changed in 2080 with the difference in climate showing that variable importance changed. In 2080 the most important variable was slope with a 74.3% contribution. This was followed by temperature seasonality which contributed to 6.5% of the modelling and elevation followed this at a 4.5% contribution. *Litoria nyakalensis* has a more distributed set of variables with the most important being the distance to water, followed by elevation and temperature seasonality. Distance to water used 20.8% of the modelling, elevation uses 17.5%, temperature seasonality uses 15.5% and land use uses 12.7%.

Table 28: Model 5: Future Projection Variable Results for Litoria species: Environmental and Climatic Variables – Elevation Included

Variable	Percent Contribution	Variable	Percent Contribution
2040		2080	
Litoria lorica		*Litoria lorica*	
Temperature seasonality	47.9	Slope	70.8
Land Use	20	Temperature seasonality	23.3
Slope	16.2	Land Use	3
Land Cover	14.9	Land Cover	2.9
Isothermality	0.5		
Litoria nyakalensis		*Litoria nyakalensis*	
Distance to Water	20.8	Slope	74.3
Elevation	17.5	Temperature seasonality	6.5
Temperature seasonality	15.5	Elevation	4.5
Land Use	12.7	Land Use	4.4
Aspect	10.6	Aspect	3.4

Table 29 shows that aspect, elevation and annual mean temperature are the most important variables for *Taudactylus acutirostris* in 2040 while aspect, temperature seasonality and land use are the most important variables for *Taudactylus rheophilus*. The importance for both species is heavily skewed with the aspect taking 59% of the modelling contribution for *Taudactylus acutirostris* and 79.3% for *Taudactylus rheophilus*. For *Taudactylus acutirostris*, aspect was followed by elevation at 12.9% and annual mean temperature with a 7.3% modelling contribution in 2040. For *Taudactylus rheophilus* aspect was also the most important variable at 79.3%, Temperature seasonality followed at 12.7%, then land use at 6.1% and land cover at 2.9%. These are the only variables important in this model. This changed in 2080 where slope became the most important variable for both species with a 53% contribution by *Taudactylus acutirostris* and an 80.3% contribution by *Taudactylus rheophilus*. This was followed by elevation with a 15.1% contribution and 10.9% contribution for *Taudactylus acutirostris*. There was also a difference in variables in 2080 for *Taudactylus rheophilus* with slope being followed by temperature seasonality at 12% and land use at 6.4%.

Table 29: Model 6: Future Projection Variable Results for Taudactylus species: Environmental and Climatic Variables – Elevation Included

Variable	Percent Contribution	Variable	Percent Contribution
2040		2080	
Taudactylus acutirostris		*Taudactylus acutirostris*	
Aspect	59	Slope	53
Elevation	12.9	Elevation	15.1
Annual Mean Temperature	7.3	Temperature Seasonality	10.9
Temperature Seasonality	7.3	Annual Mean Temperature	6.7
Land Use	3	Land Use	4.5
Taudactylus rheophilus		*Taudactylus rheophilus*	
Aspect	79.3	Slope	80.3
Temperature Seasonality	12.7	Temperature Seasonality	12
Land Use	6.1	Land Use	6.4
Land Cover	1.9	Land Cover	1.3
Isothermality	0		

The most important variables for *Litoria lorica* were temperature seasonality in 2040 which contributed to 47.9% of the modelling, land use which contributed 20% and slope which contributed 16.2% (Table 30). The most important variables for *Litoria nyakalensis* in 2040 were mean temperature of the wettest, distance to water and temperature seasonality. These contributed 30.7%, 19% and 14.3%. Nothing changed for *Litoria lorica* in model 7 when compared to model 5 with temperature seasonality still using 47.9% and followed by land use and slope. With the removal of elevation, the more important variables become mean temperature of the wettest quarter at 30.7%, in front of distance to water at 19% and temperature seasonality at 14.3%. *Litoria nyakalensis* relies on a variety of factors including distance to water and mean temperature of the wettest quarter as well as temperature seasonality. In 2080 the variables that contribute the most to the modelling for *Litoria lorica* were slope, temperature seasonality and land use. Slope was the main contributor with 70.8% of the modelling, followed by temperature seasonality at 23.3% and land use at 3%. This is a change from temperature seasonality being the most important variable to the second most important with land use and land cover also being bumped down. The modelling for *Litoria nyakalensis* shows that slope is now also the most important variable with a 75.2% contribution. This was followed by mean temperature of the wettest quarter with a 5.8% and land use with a 5.1% contribution.

Table 30: Model 7: Future Projection Variable Results for Litoria species: Environmental and Climatic Variables – Elevation Excluded

Variable	Percent Contribution	Variable	Percent Contribution
2040		2080	
Litoria lorica		*Litoria lorica*	
Temperature Seasonality	47.9	Slope	70.8
Land Use	20	Temperature Seasonality	23.3
Slope	16.2	Land Use	3
Land Cover	14.9	Land Cover	2.9
Isothermality	0.5		
Litoria nyakalensis		*Litoria nyakalensis*	
Mean Temperature of the Wettest Quarter	30.7	Slope	75.2
Distance to Water	19	Mean temperature of the Wettest Quarter	5.8
Temperature Seasonality	14.3	Land Use	5.1
Land Use	12.6	Temperature Seasonality	3.3
Aspect	10.4	Distance to Water	3.3

Table 31 indicates that for *Taudactylus acutirostris* in 2040 the most important variables are mean temperature of the wettest quarter, annual mean temperature and temperature seasonality. These variables contributed 34.4%, 23% and 22.2%. For *Taudactylus rheophilus* the most important variables in 2040 are temperature seasonality, land use and land cover. Temperature seasonality contributed 63.7% to the modelling, land use contributed 25.6% to the modelling and land cover contributed 7.4% to the modelling. In 2080 the most important variables for *Taudactylus rheophilus* are slope, temperature seasonality and land use, a distinct shift. For *Taudactylus acutirostris* they are mean temperature of the wettest quarter, annual mean temperature and temperature seasonality. The modelling shows that slope gave a 50.7% contribution to the modelling, followed by annual mean temperature at 15.4% and mean temperature of the wettest quarter at 13.4% for *Taudactylus acutirostris* in 2080 while for *Taudactylus rheophilus* the variables contributed 80.3% (slope), 12% (temperature seasonality) and 6.4% (land use).

Table 31: Model 8: Future Projection Variable Results for Taudactylus species: Environmental and Climatic Variables – Elevation Excluded

Variable	Percent Contribution	Variable	Percent Contribution
2040		2080	
Taudactylus acutirostris		*Taudactylus acutirostris*	
Mean Temperature of the Wettest Quarter	34.4	Slope	50.7
Annual Mean Temperature	23	Annual Mean Temperature	15.4
Temperature Seasonality	22.2	Mean Temperature of the Wettest Quarter	13.4
Land Use	8.1	Temperature Seasonality	11.3
Distance to Water	3.7	Land Use	4.5
Taudactylus rheophilus		*Taudactylus rheophilus*	
Temperature seasonality	63.7	Slope	80.3
Land Use	25.6	Temperature seasonality	12
Land Cover	7.4	Land Use	6.4
Mean temperature of the Wettest Quarter	2.6	Land Cover	1.3
Aspect	0.7		

5.3.3 Model Outputs

Model 3 shows there is a significant area of highly suitable habitat to the north of latitude -17.17° of the study area for *Litoria lorica* which extends parallel down the coast. As shown in figure 28, the corresponding area under this is an area of moderately suitable habitat followed by a matching area of low suitability further south. For *Litoria nyakalensis* (Figure 29) the most suitable habitat is on the far western boundary between -16.2° and -16.35° with moderately suitable habitat extending from -16.16° to -17.75° but not stretching to the coast. In this model the area below -18.5° is unsuitable for both species.

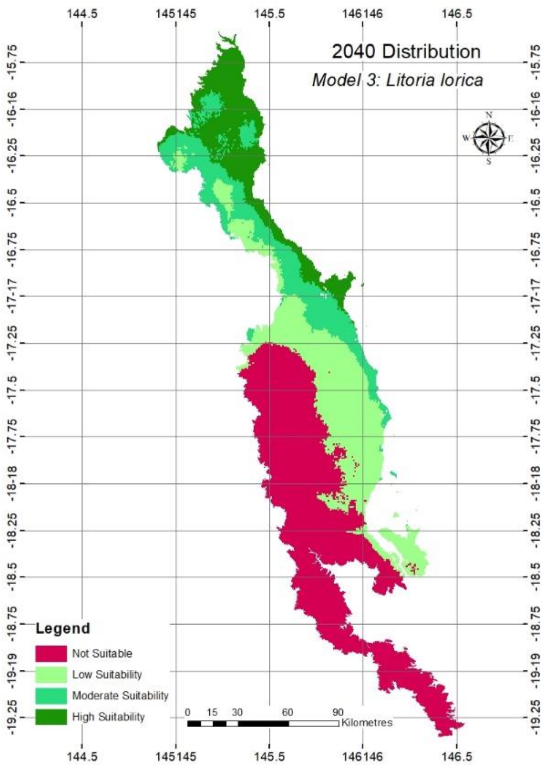


Figure 28: Model 3 (2040) output results for Litoria lorica

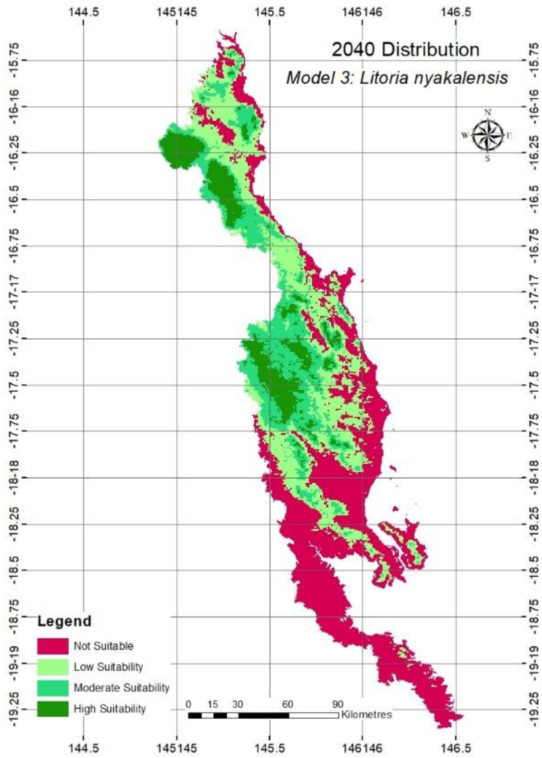


Figure 29: Model 3 (2040) output results for Litoria nyakalensis

Figure 30 shows that the suitable habitat in 2080 has little difference to the 2040 modelling with the high suitability habitat not extending past latitude -17.17° and extending parallel with the coastline. In 2080 there is no suitable habitat lower than latitude -18.1°. For *Litoria nyakalensis* (Figure 31) the unsuitable habitat runs parallel to the coastline while the amount of suitable habitat increases with the distance from the coast. The majority of the high suitability habitat is found west of longitude 145.75° between latitudes -17.75° and -16.2°. There is little change here from the 2040 modelling.

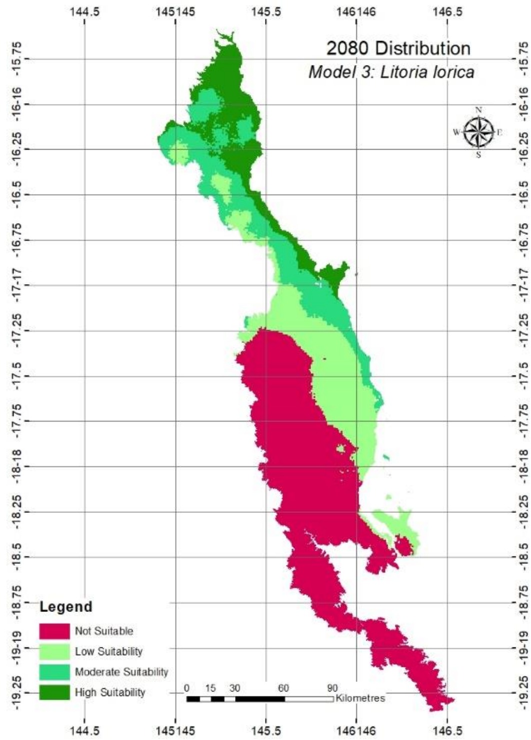


Figure 30: Model 3 (2080) output results for Litoria lorica

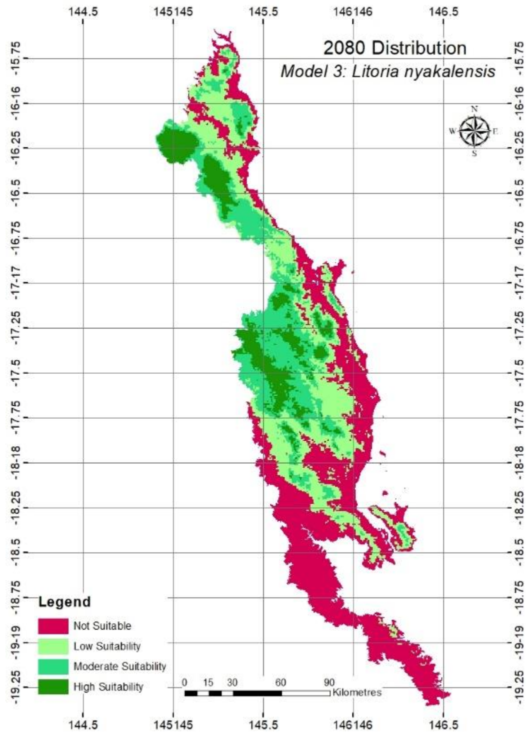


Figure 31: Model 3 (2080) output results for Litoria nyakalensis

Model 4 shows the suitability of habitat under climatic conditions in 2040 for the *Taudactylus* species. *Taudactylus acutirostris*, as shown in Figure 32, has patchy distribution from the western edge across to longitude 146° with the highly suitable habitat concentrated in a small patch from latitude -16.5° to -16.1°. These patches are highly fragmented with large patches of not suitable habitat separating them. It is the opposite for *Taudactylus rheophilus* (Figure 33) with the only not suitable habitat found below latitude -18.1°. The high suitability habitat is found above latitude -16.5° with a small line extending down and parallel to the coast.

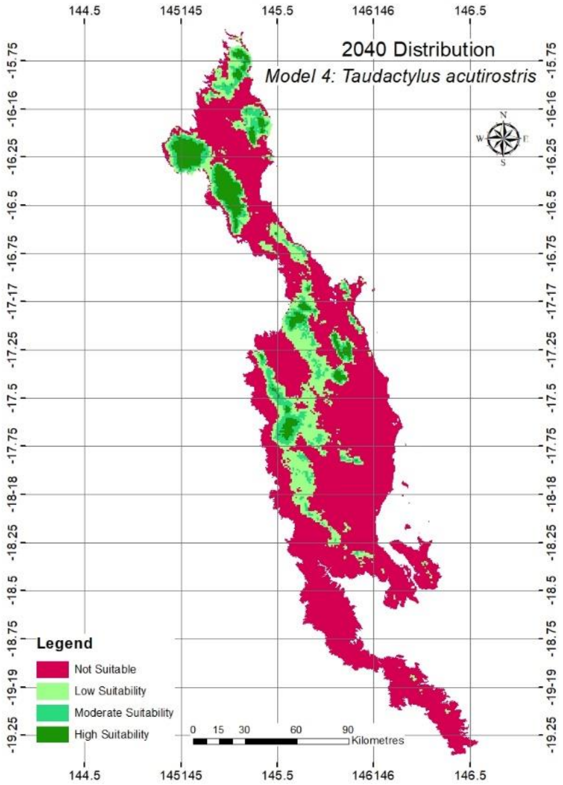


Figure 32: Model 4 (2040) output for Taudactylus acutirostris

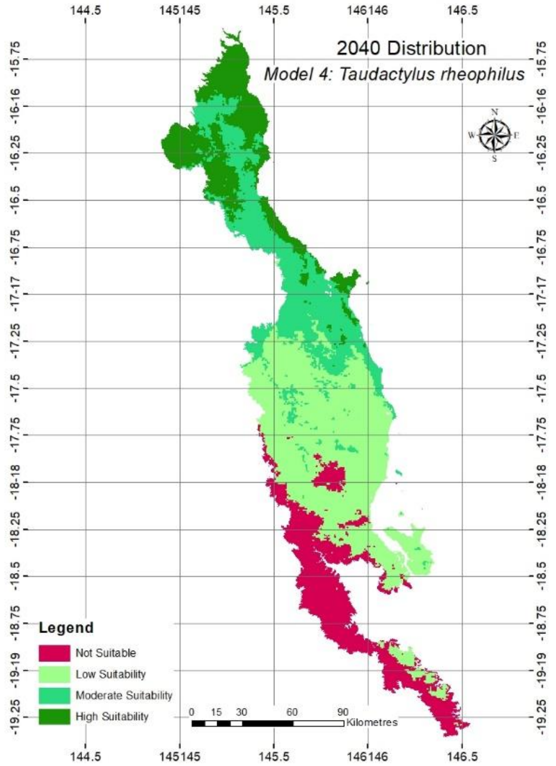


Figure 33: Model 4 (2040) output for Taudactylus rheophilus

The 2080 outputs show little difference to the suitable habitat from the 2040 modelling with the majority of the high suitability habitat for *Taudactylus acutirostris* (Figure 34) still between latitudes -16.5° and -16.1°. For *Taudactylus rheophilus* (Figure 35) the low suitability habitat begins at latitude -18.5° and continues north before becoming moderate suitability habitat around latitude -17.25°. Latitude -16.5° is where the high suitability begins and continues north.

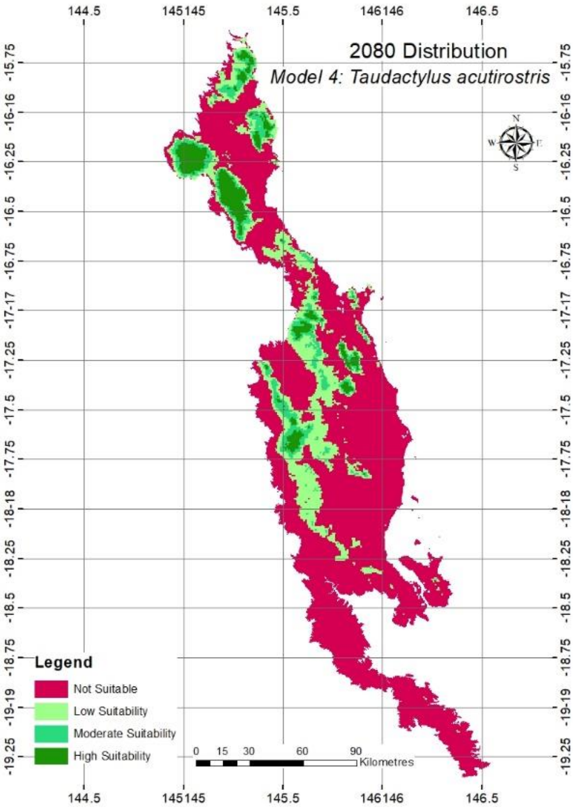


Figure 34: Model 4 (2080) output for Taudactylus acutirostris

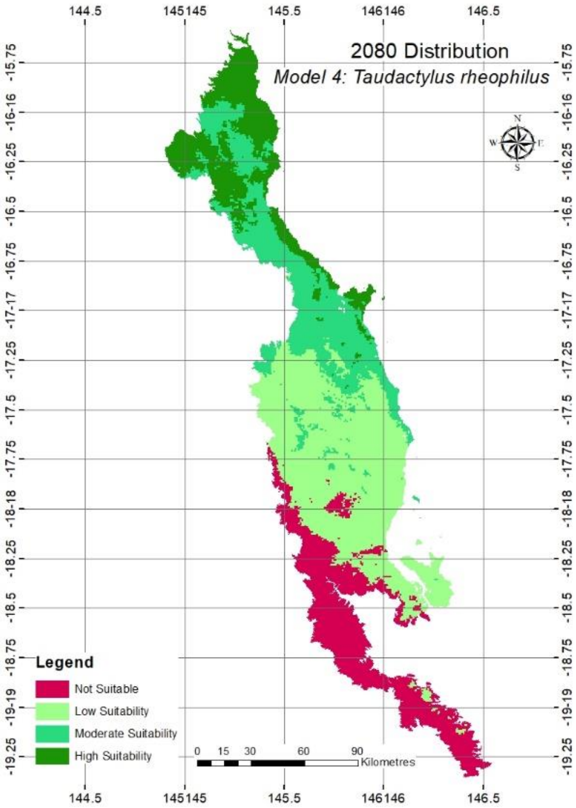


Figure 35: Model 4 output (2080) for Taudactylus rheophilus

Figure 36 shows the contraction of suitable habitat for *Litoria lorica*. Habitat considered not suitable now extends to latitude -17.2° with scattered areas of suitable habitat to -16.5°. Above this is a patch of mixed moderate and high suitability that extende to the northern edge of the study area.

For *Litoria nyakalensis* (Figure 37) there is a similar mixed suitability patch but this centred within the study area between latitudes -18.2° and -16.25°.

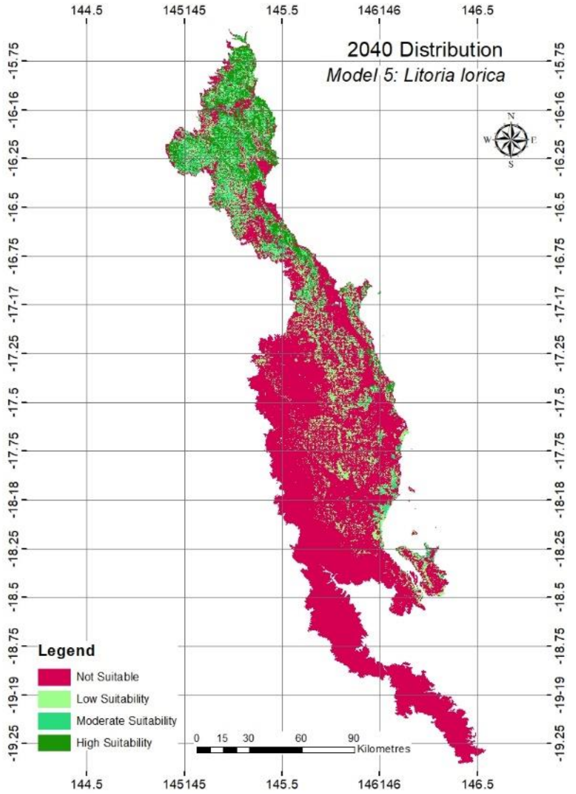


Figure 36: Model 5 (2040) output for Litoria lorica

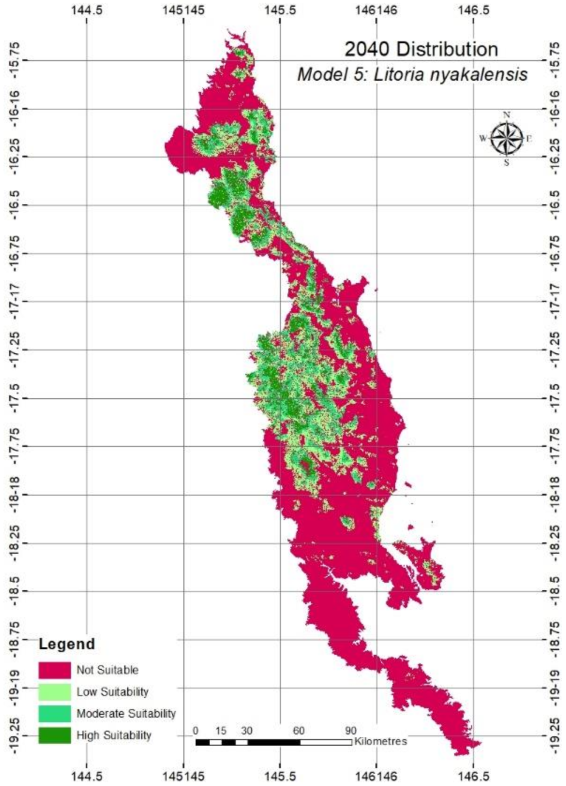


Figure 37: Model 5 (2040) output for Litoria nyakalensis

Figure 38 shows a significant decline from the 2040 output with little suitable habitat available. Only a few small patches of low suitability habitat remains above latitude -16.5° with another small patch running down the length of the coastline to latitude -16.75°. For *Litoria nyakalensis* there appears to be no suitable habitat in this model (Figure 39).

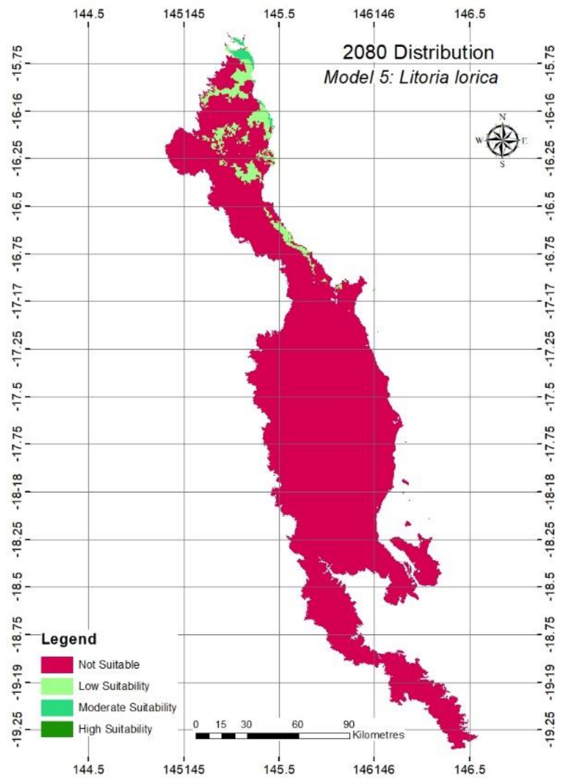


Figure 38: Model 5 (2080) output for Litoria lorica

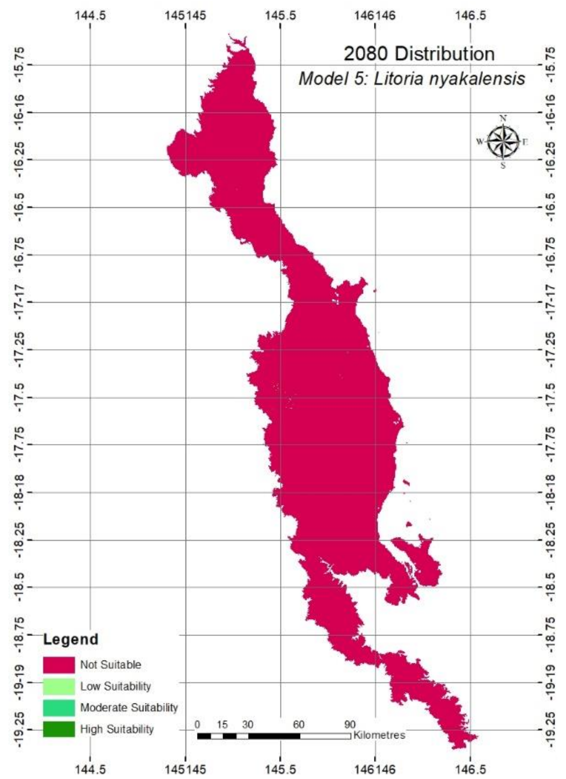


Figure 39: Model 5 (2080) output for Litoria nyakalensis

Figure 40 shows the 2040 model output for *Taudactylus acutirostris* based on combined climate and environmental data. The results show the amount of suitable habitat has visibly decreased but a patch of high suitability habitat remains on the western edge from latitudes -16.5° to -16.25°.

For *Taudactylus rheophilus* (Figure 41) it is the opposite with much of study remaining suitable. Much of the area above latitude -17.5° is either moderate or high suitability with large areas of low suitability below this area. The suitability is reduced below -18.5° with little suitable habitat remaining.

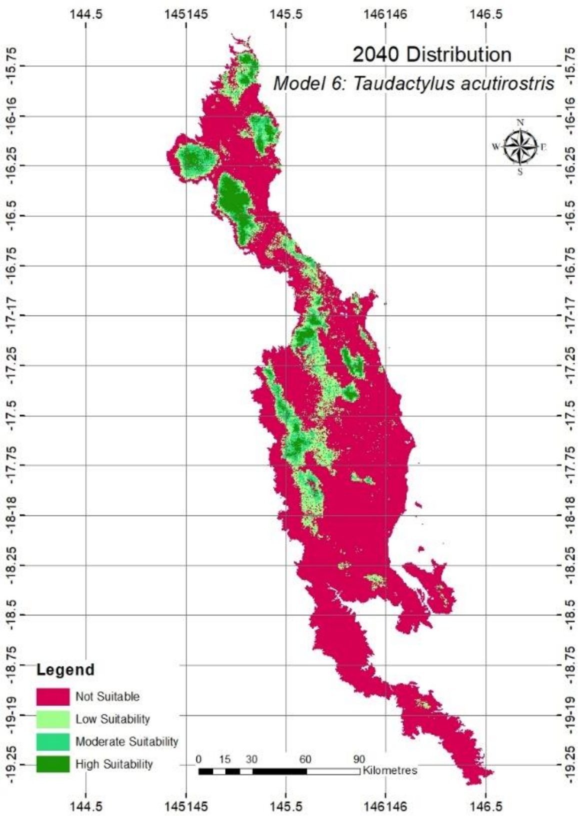


Figure 40: Model 6 (2040) output for Taudactylus acutirostris

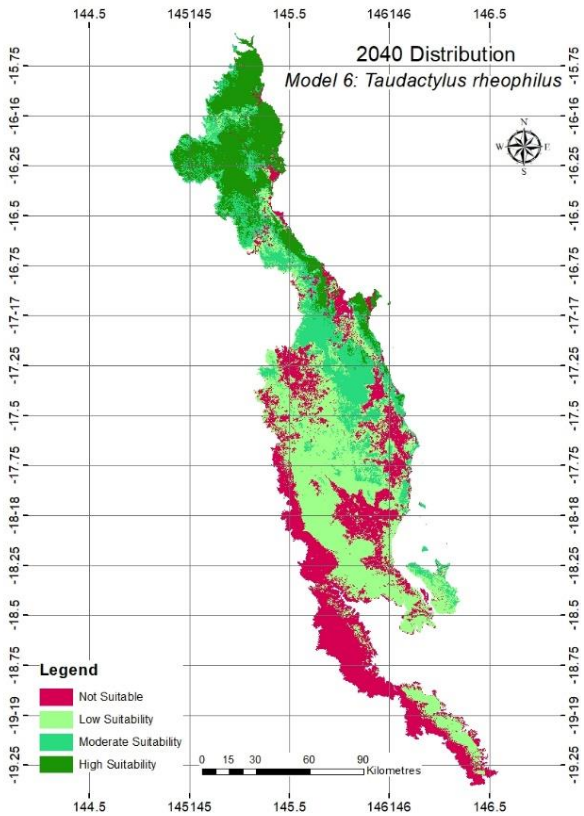


Figure 41: Model 6 (2040) output for Taudactylus rheophilus

Figures 42 and 43 detail the lack of suitable habitat for either *Taudactylus* species with Model 6 by 2080. There is one small patch remaining for *Taudactylus acutirostris* (Figure 42) at -16.5° and 145.25°. This patch is low suitability and is very small. For *Taudactylus rheophilus* (Figure 43) there is a patch of low suitability habitat extending from latitude -15.5° to -16.25° hugging the coastline.

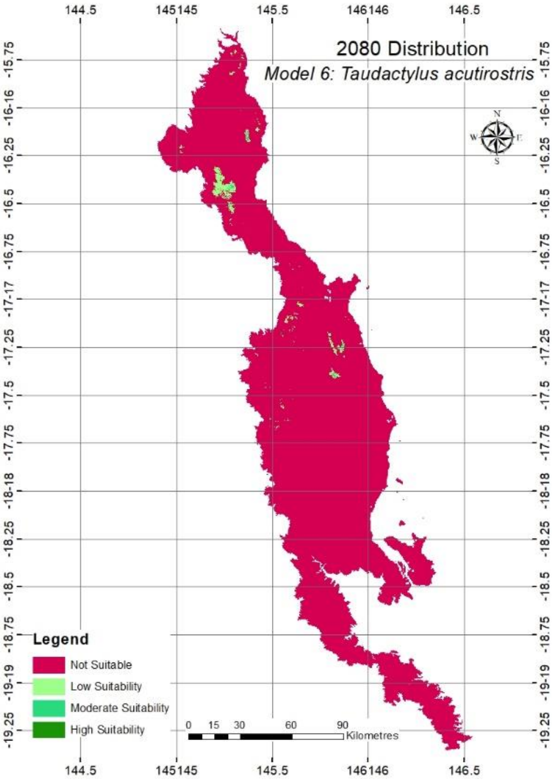


Figure 42: Model 6 (2080) output for Taudactylus acutirostris

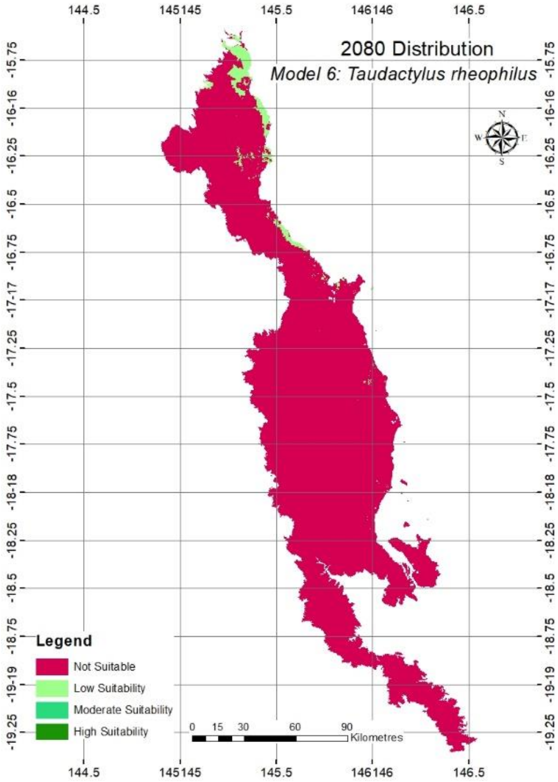


Figure 43: Model 6 (2080) output for Taudactylus rheophilus

Figure 44 shows the most suitable habitat for *Litoria lorica* in 2040 is above latitude -16.5° with the southern and mid part of the Wet Tropics not suitable. The suitable habitat for *Litoria nyakalensis* on the northwest edge has shrunk and parts that were formerly highly suitable are now unsuitable. There is still a significant part of the habitat that appears to be suitable between latitudes -16.25° and -18.18°. In 2080 this changes dramatically as the climate changes with all the suitable habitat disappearing for *Litoria nyakalensis* (Figure 45) and only a small patch of marginal habitat remaining for *Litoria lorica* in the far north of the study area.

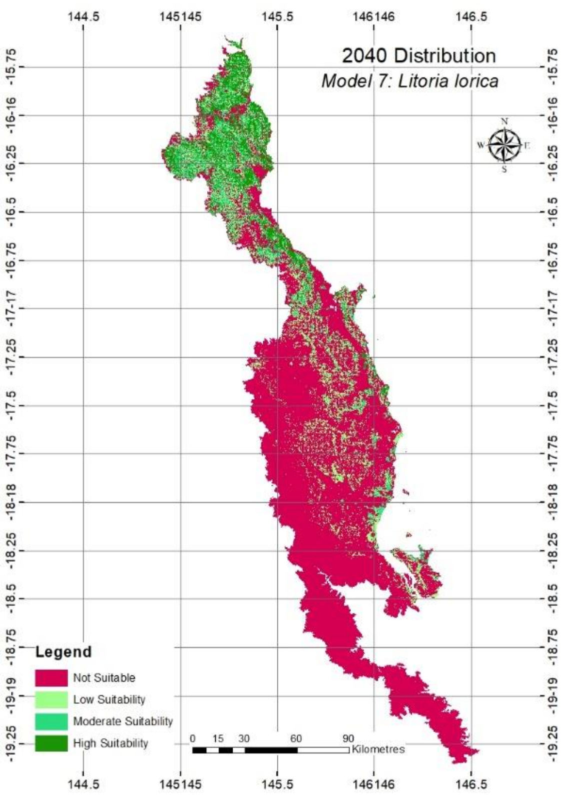


Figure 44: Model 7 (2040) output for Litoria lorica

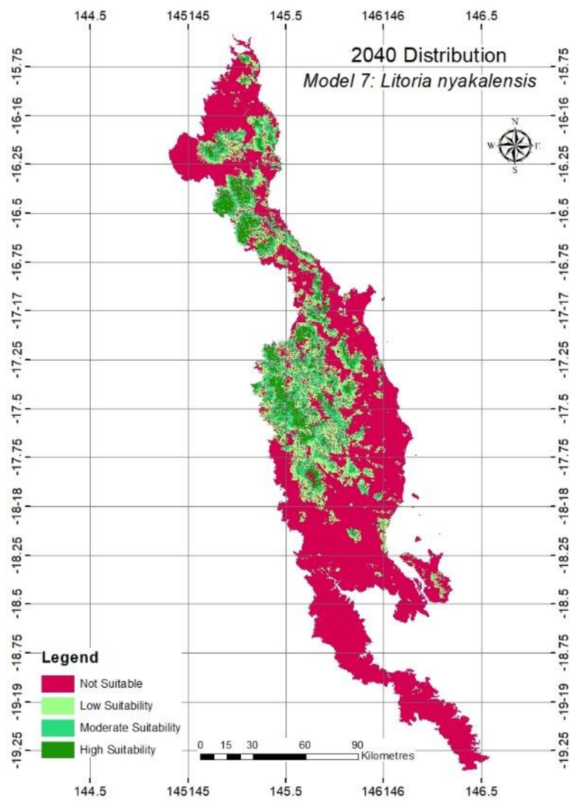


Figure 45: Model 7 (2040) output for Litoria nyakalensis

By 2080 there will only be low suitability habitat remaining for *Litoria lorica* as shown in figure 46. This does not extend past latitude -16.75° and only exists in small, spaced patches. Figure 47 indicates there will be no suitable habitat for *Litoria nyakalensis* by 2080.

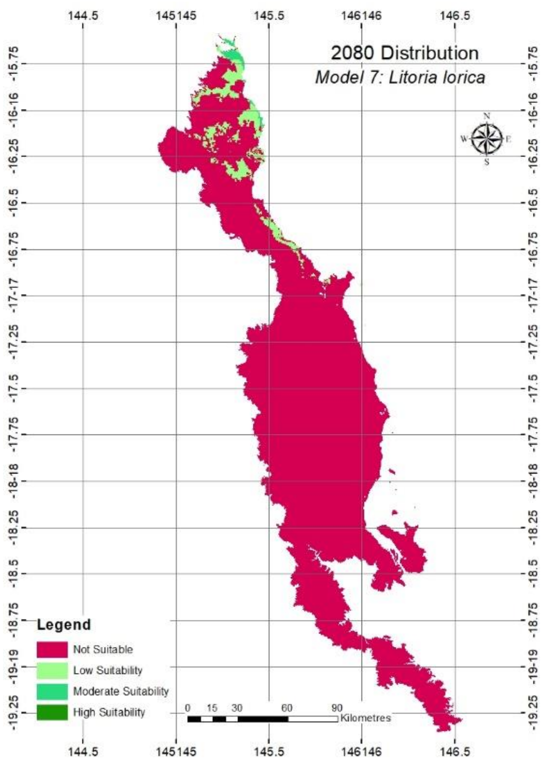


Figure 46: Model 7 (2080) output for Litoria lorica

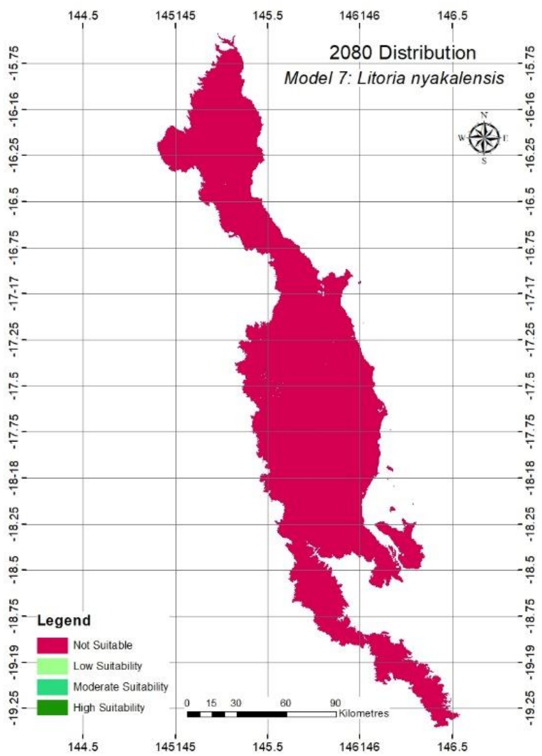


Figure 47: Model 7 (2080) output for Litoria nyakalensis

Figure 48 indicates there will only be small patches of highly suitable habitat for *Taudactylus acutirostris* by 2040. There is little change in this model compared to model 6. It is different for *Taudactylus rheophilus* (Figure 49) as it is more affected by the removal of elevation. There is a large patch of highly suitable habitat extending across the study area above latitude -17.2° with moderate suitability habitat extending down to -18°. Most of the habitat appears green indicating most of the habitat is suitable in some form.

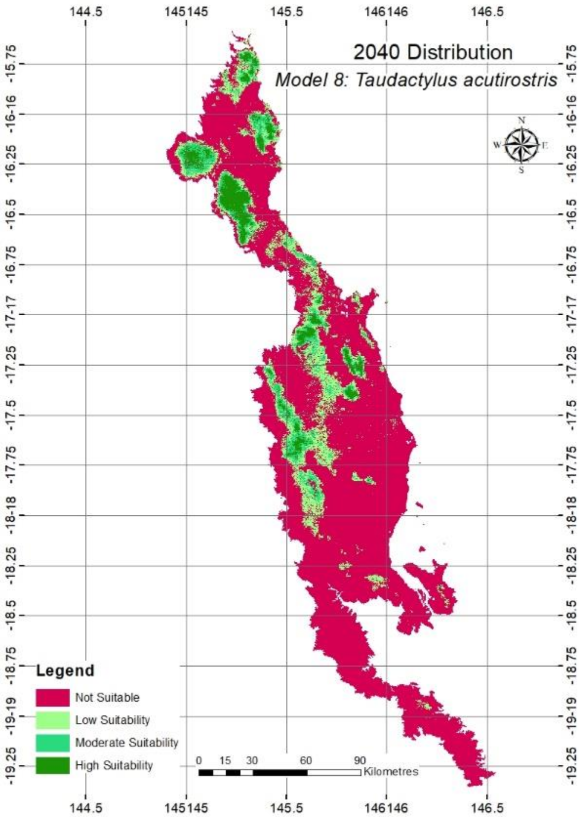


Figure 48: Model 8 (2040) results for Taudactylus acutirostris

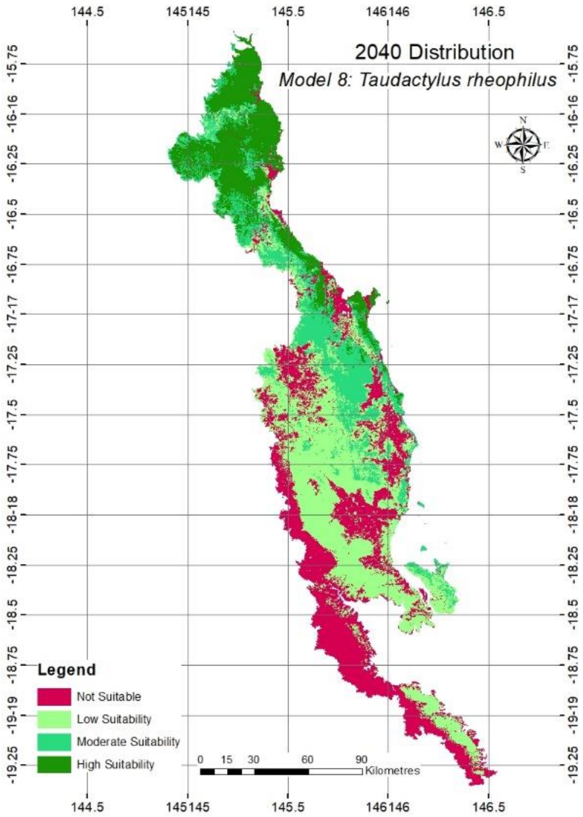


Figure 49: Model 8 (2040) output for Taudactylus rheophilus

There is little change in suitable habitat for either species in the 2080 modelling with one small patch potentially suitable for both species. *Taudactylus acutirostris* (Figure 50) has a small patch at -16.5° and 145° while *Taudactylus rheophilus* (Figure 51) has a patch at 145.25° and extending from the tip of the study area to -16.75°.

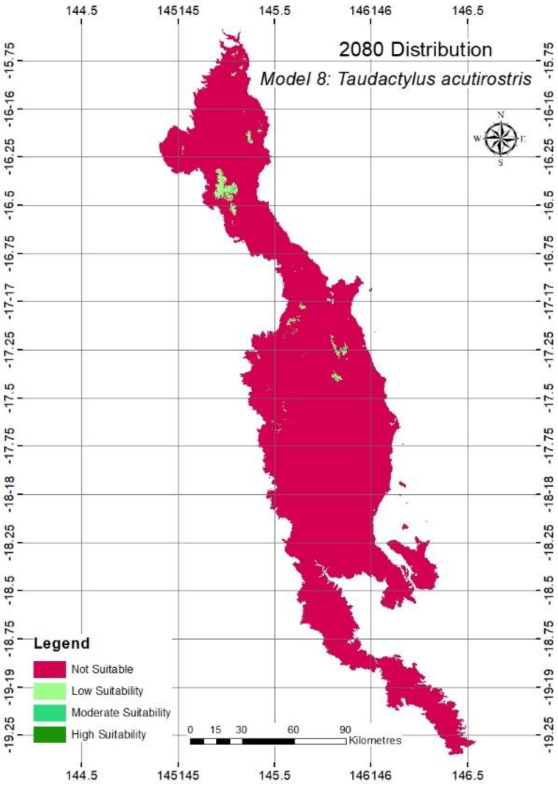


Figure 50: Model 8 (2080) output for Taudactylus acutirostris

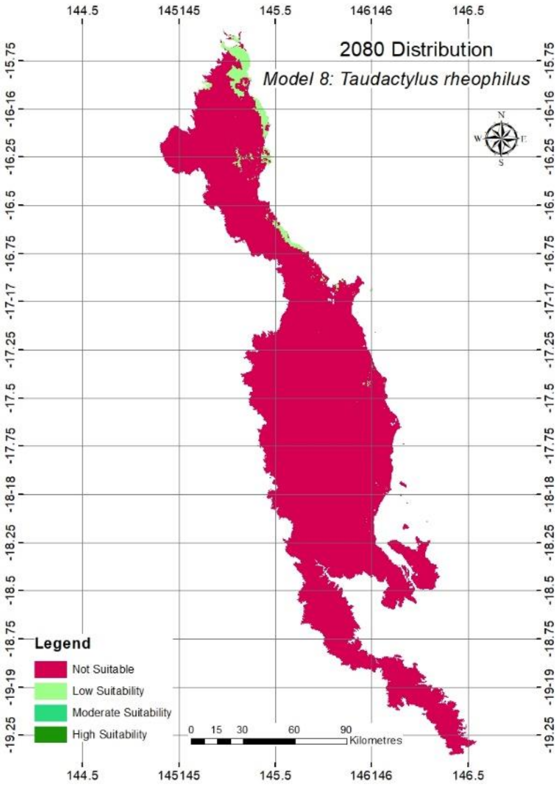


Figure 51: Model 8 (2080) output for Taudactylus rheophilus

5.3.4Future Climate Projection Model Validation

The Area under the ROC (Receiver Operating Characteristics) Curve (AUC) determines the probability of the accuracy of the models, therefore, the higher the number given as the AUC score, the better the model. The AUC scores are between 0 and 1 with the scores closer to 1 being the more accurate.

Figure 52 gives a representation of the AUC from the 2040 Future Climate Modelling. In the 2040 modelling there are only two models that gave AUC scores under 0.7, as seen in figure 52, both for *Litoria nyakalensis*. *Taudactylus acutirostris* is shown to consistently have the highest AUC score averaging 0.88 while *Litoria lorica* average 0.7, *Litoria nyakalensis* averaged 0.73 and *Taudactylus rheophilus* averaged 0.74. Overall the models had an accuracy of 0.76.

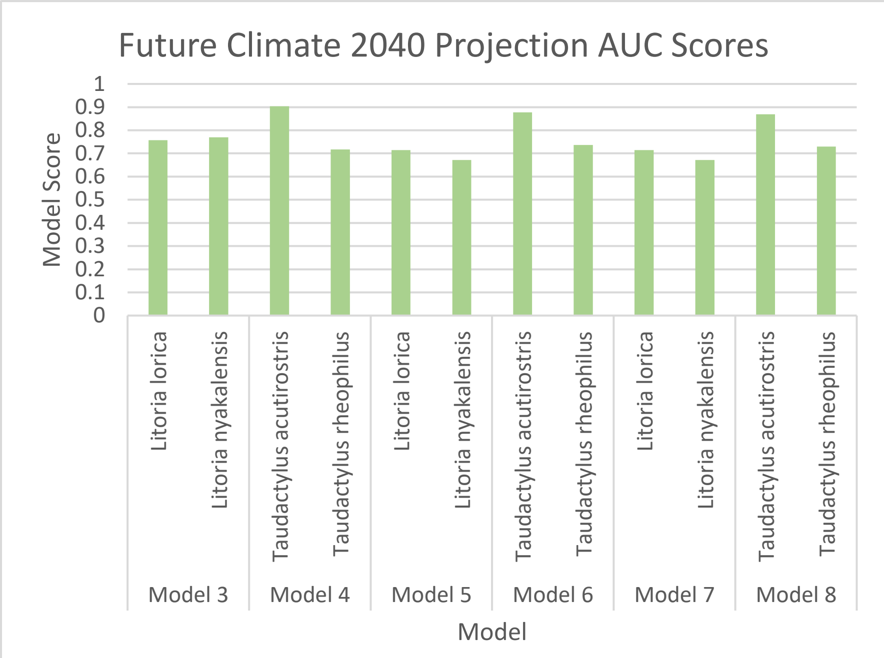


Figure 52: The AUC modelling scores for the 2040 Future Climate Distribution

In 2080 the average AUC is 0.89 for *Taudactylus acutirostris*, 0.8 for *Litoria lorica*, 0.7 for *Litoria nyakalensis* and 0.79 for *Taudactylus rheophilus*. Again the lowest scores were for *Litoria nyakalensis* and the scores for *Litoria lorica* have improved. Overall the modelling for 2080 averaged a score of 0.8 showing that the probability of the models being accurate is high.

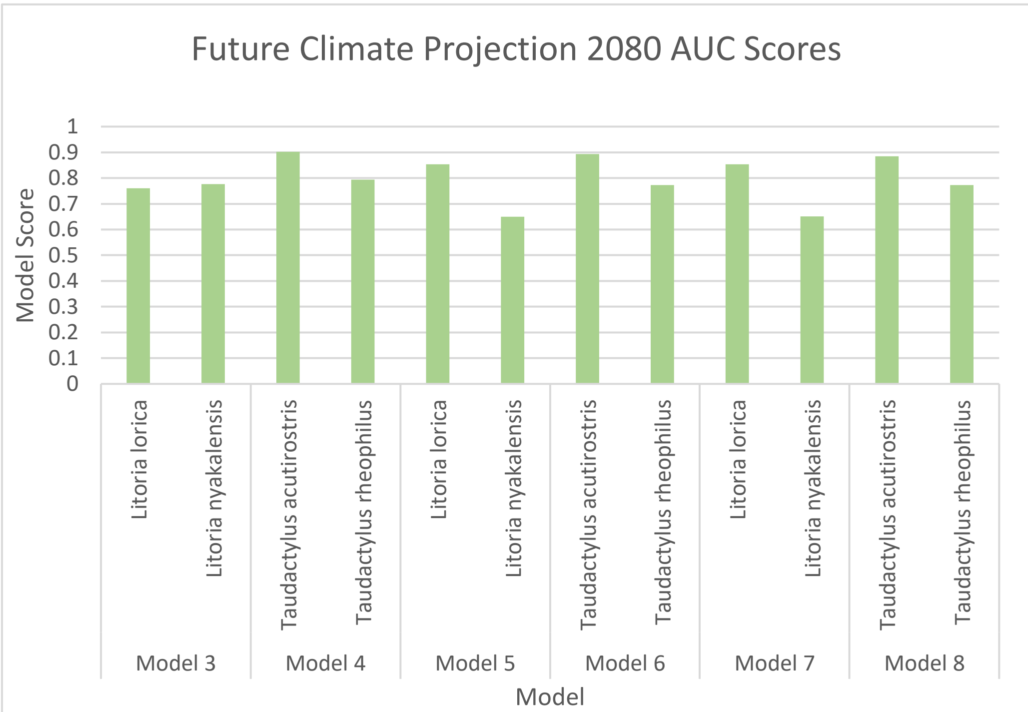


Figure 53: The AUC modelling scores for the 2080 Future Climate Distribution

5.4 Discussion

5.4.1 Habitat Availability

This chapter has detailed the similarities and differences between the potential habitat in the years 2040 and 2080 compared to the current potential distribution. Little literature appears to be available on the current and future climatic requirements of these frogs and therefore there are few papers for reference. This chapter compares the results obtained in this study for the future distribution to those of Chapter 4 (Current Species Distribution of *Litoria* and *Taudactylus* Frogs in the Wet Tropics) to understand the impact of climate change on the distribution of these frogs. Under the most optimistic SSP (SSP126), it can be seen that there is still a significant decrease in the suitability of habitat by 2080. In the climate variables only models of the 2040 there was seen to be a change from the current distribution modelling. For *Litoria lorica*, this change was an increase of 4,297 hectares (0.2%) while for *Litoria nyakalensis* it was a decrease of 7,546 hectares (0.4%). *Taudactylus acutirostris* saw a decrease of 4,839 hectares (0.3%) while *Taudactylus rheophilus* saw an increase of 33,762 hectares (1.9%).

The addition of environmental variables further altered the amounts of suitable habitat with *Litoria lorica* seeing a decrease from the current distribution modelling of 35,661 hectares (2%). *Litoria nyakalensis* saw a decrease of 1,491 hectares (0.1%) and *Taudactylus acutirostris* a decrease of 1,348 hectares. *Taudactylus rheophilus*, however, saw an increase of 88,218 hectares (5%). It is clear that *Taudactylus rheophilus* will benefit the most from a small increase in the temperature while *Litoria lorica* and *Taudactylus acutirostris* will suffer. This change in area is primarily due to the increase in temperature which can be seen to be an important factor in these models.

In 2080, there is a widespread decrease resulting a loss of all high and moderately suitability habitat for all species. Figures 54 and 55 show the change in distribution across the years modelled for *Litoria lorica* and *Litoria nyakalensis*.

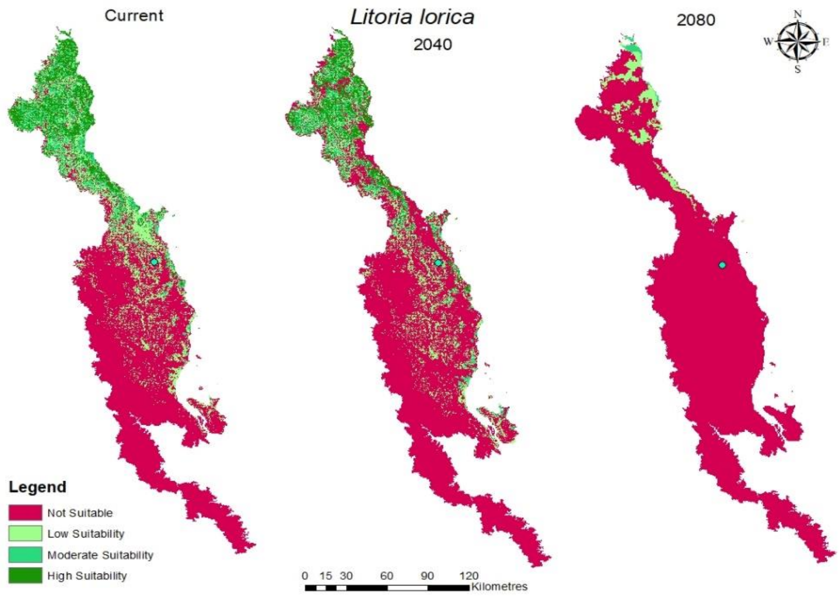


Figure 54: The change in distribution from the current distribution to 2040 for Litoria lorica

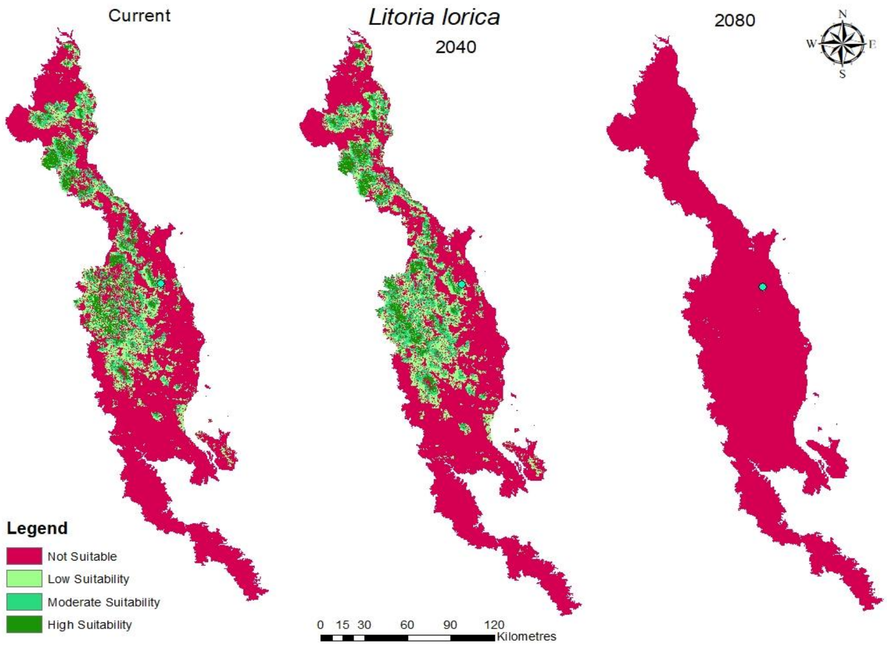


Figure 55: The change in distribution form the current distribution to 2080 for Litoria nyakalensis

With elevation excluded, in 2040 the suitable habitat reduced to 92,082 hectares (5% of the Wet Tropics) for *Litoria nyakalensis* and 128,641 hectares (7.2%) for *Litoria lorica* but in 2080 this was further reduced to 0% of the habitat for both species. The impact of a changing climate is shown to have different outcomes for the two *Taudactylu*s species used in this study. The area increased for *Taudactylus acutirostris* and created 572 hectares of more suitable habitat, leading to 81,814 hectares (4.6% of the habitat) for *Taudactylus acutirostris*. It also increased for *Taudactylus rheophilus* in which 88,218 hectares of highly suitable habitat was created by 2040, making 304,153 hectares (17.1%). This shows that while both species will benefit *Taudactylus rheophilus* will benefit more from climate change in 2040 and the changing climate will allow more of the habitat to become highly suitable for these species. This is a contrast to the information given by WTMA (2016) who state *Taudactylus rheophilus* will suffer from climate change. In 2080 there was 98.7% of the habitat that was not suitable for *Taudactylus acutirostris* and 97.3% unsuitable for *Taudactylus rheophilus*. There was no moderately or highly suitable habitat for either species in 2080.

Taudactylus rheophilus continued to increase its habitat when elevation was excluded as a factor with a rise of 51,672 hectares. In contrast, 894 hectares is by how much the highly suitable habitat of *Taudactylus acutirostris* decreased. This shows that elevation is more of a factor for *Taudactylus acutirostris* than it is for *Taudactylus rheophilus* in 2040 modelling. The modelling for 2080 showed that the habitat continued to decrease for *Taudactylus acutirostris* (Figure 56) with 1,348 hectares less but the increase in suitable habitat was sustained for *Taudactylus rheophilus* (Figure 57) which to 304,153, a rise of 51,702 hectares. The results for *Litoria lorica* show that the habitat decreased by a further 35,164 hectares while for *Litoria nyakalensis* the highly suitable habitat decreased by 65,570 hectares.

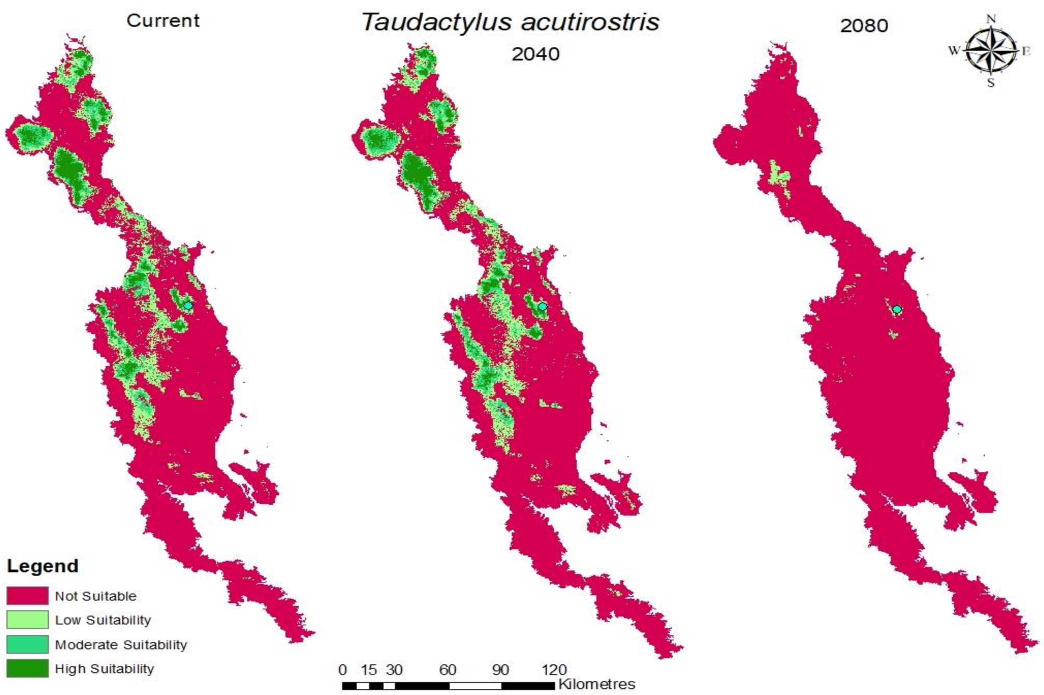


Figure 56: The change in distribution from the current distribution to 2080 for Taudactylus acutirostris

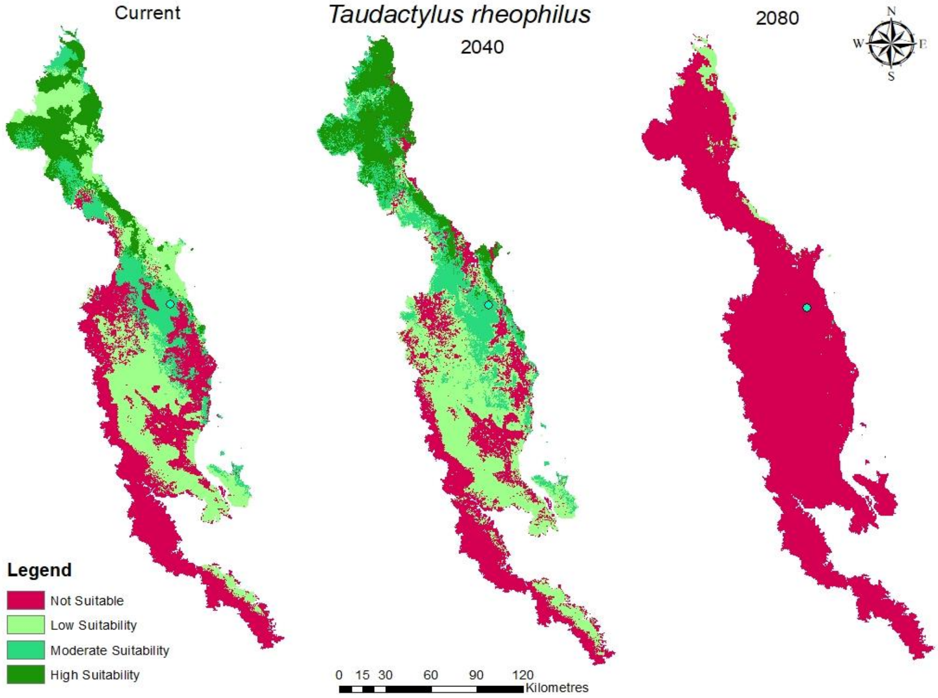


Figure 57: The change in distribution from the current distribution to 2080 for Taudactylus rheophilus

5.4.2 Future Climate Habitat Requirements

The results show that in 2040 *Litoria lorica* is a frog that prefers habitat with temperatures between 23°C and 28°C with low temperature seasonality and a low mean diurnal temperature range. *Litoria lorica* prefers habitat with little change in the temperature. It appears from the modelling that *Litoria lorica* prefers the areas of the wet tropics that receive higher daily temperatures with little variation. Hoskin and Puschendorf (2014) voice the idea of *Litoria lorica* preferring hotter, drier forested areas but give no details on what constitutes 'hot' and 'dry' and therefore this cannot be corroborated. The mean temperature of the wettest quarter is between 23°C and 29°C for this species and little change in temperature between seasons. The isothermality for this species does not appear to affect habitat suitability as the levels vary by 53% to 58%. This is similar with temperature seasonality as there are high levels of suitability between 22% and 28%. *Litoria lorica* is a species that prefers elevation up to 1200m and habitat with tree cover across areas slated as nature conservation, managed resource protection, waste treatment and disposal or native grazing vegetation. This means that their habitat limits are pushed to higher elevations by 2040. In 2080 this changed with the increased alteration of the climate. As *Litoria lorica* is primarily reliant on temperature seasonality it is clear that changes in the variability of temperate will cause a significant risk to these frogs. When compared to the results of the 2080 the moderately suitable class must be used as there is no longer any highly suitable habitat. In 2080, the results show the most optimal (moderately suitable habitat) temperature for *Litoria lorica* is between 24°C and 28°C with a diurnal temperature range of 6 – 8°C and a temperature seasonality rate of less than 2.2%. The mean temperature of the wettest quarter is between 25°C and 29°C. The annual precipitation in 2080 is between 2000mm and 4000mm.

In 2040 with the change in climate, *Litoria nyakalensis* is now reliant on temperatures between 20°C and 26°C with a diurnal temperature range of 3°C to 5°C and an isothermality of 53% to 58%. The average temperature of the wettest quarter is preferably between 22°C and 26°C with a seasonality of 240 – 300 and an annual precipitation rate of 2000 – 4000mm per year. This can be compared to the results of the current climate data as drier and hotter with a 4°C temperature rise and less rain by 1000mm. *Litoria nyakalensis* is shown to be reliant on lower temperatures and therefore higher elevations. In 2080 the climatic conditions change and 100% of the high suitability temperature is below 20°C meaning the optimal temperatures are at the very lowest of the new climatic conditions. The diurnal temperature range has risen to 9°C, showing that *Litoria nyakalensis* requires high seasonality in order to thrive, with the isothermality between 53% and 55%. The temperature seasonality is now between 2.8% and 3% with the mean temperature of the wettest quarter between 23°C and 25°C. *Litoria nyakalensis* also prefers 2000mm per year rainfall in the 2080 projection.

In 2040 the annual average temperature for *Taudactylus acutirostris* is between 20 and 26°C with a diurnal temperature range of 7°C – 9°C and a seasonality of 2.8%. *Taudactylus acutirostris* prefers an annual rate of rainfall of 2000 – 4000mm in 2040 and the mean temperature of the wettest quarter is shown to be in the optimal ranges when between 23 and 27. The isothermality is between 50 and 58. In 2080 this changes due to the altered climate. The results are slightly more promising for *Taudactylus acutirostris* in 2080 with the optimal temperature being spread between 18°C and 26°C with the most optimal habitat between 22°C and 26°C. The mean diurnal temperature is between 7°C and 10°C with an isothermality variation of 50 to 55. The temperature seasonality is restricted to 2.8% to 3%. The mean temperature of the wettest quarter is 25°C to 27°C. This shows the climatic conditions have become narrower and it will be harder for this species in the future.

Taudactylus rheophilus prefers warmer temperatures in 2040 with these temperatures between 22 and 26°C with an annual precipitation rate of 2000 – 3000mm, a diurnal temperature range of 7 – 10°C and an isothermality index of 50 – 58% with temperature seasonality between 2.4°C and 2.8°C. The average temperature of the wettest quarter for *Taudactylus rheophilus* is between 25 and 29°C. In 2080 the optimal temperature range was restricted to 24°C and higher. The diurnal temperature range was between 7°C and 9°C. The isothermality was limited to 53 to 55% and the temperature seasonality was between 2.2% and 2.4%. The mean temperature of the wettest quarter was between 24°C and 30°C. The annual precipitation was 1000 to 3000mm.

It is recommended that the areas outlined in this study are the focus of future searches for these species. Searches for *Taudactylus rheophilus* and *Litoria lorica* should focus on the northern area of the Wet Tropics while searches for *Litoria nyakalensis* and *Taudactylus acutirostris* should focus on the western edge. For *Taudactylus rheophilus* the searches should remain in the lower elevations and for *Litoria nyakalensis* the searches should be restricted to above 700m. The southern part of the Wet Tropics appears to be less suitable for these species as does the area towards the coast. The patches of highly suitable habitat shown in the figures in the results sections should provide the base for planning surveys. Manual surveys should be limited as much as possible to avoid damage to the environment yet cannot be avoided altogether. The figures 52, 53, 54 and 55 above show the change in potential distribution under changed climatic conditions with each frog showing a drastic decline by 2080. The areas shown in green in each model are those areas where future searches should be directed. The darker areas are more suitable while the red shows areas deemed not suitable.

The area most suitable for *Litoria lorica* is in the north of the Wet Tropics but is reduced to small patches of low suitability on the northernmost point in 2080. For this species the areas that should be searched are those above latitude -16°, particularly those areas defined as nature conservation.

For *Litoria nyakalensis* the priority areas are those over 700m elevation and can be seen in figure 55 as those areas in darker green. This species prefers cooler temperatures and will not fare well with climate change as shown by the 2080 modelling.

Taudactylus acutirostris is shown to have segmented patches of highly suitable habitat to the west and north of the study area. These should be prioritised for searches for this species. As shown by the green dot to the west of the central study area (Figure 56), Mt Bellenden Ker remains one of the few patches of suitable habitat in 2080.

Due to the difference in habitat preferences there is unlikely to be any area where all four of these frog species are found and therefore different approaches will be needed to aid these species in the future.

CHAPTER 6: CONCLUSION

This thesis has challenged some preconceptions and assumptions associated with the environmental constraints of both *Litoria* frogs and *Taudactylus* frogs. Some assumptions regarding their habitat and potential distribution have been contradicted. Areas thought to be the only habitat for these species are now being seen as one of many spots where these frogs can be hiding from humanity. It is possible that these species are living undiscovered in a part of the Wet Tropics not yet searched. Previously, *Litoria nyakalensis* was thought to only live on the tops of certain mountains (Department of Climate Change; Energy; Environment and Water 2022d) but this study has shown a larger area of highly suitable habitat that has potentially gone unsearched. *Litoria lorica* was previously thought to be restricted to higher elevations (Department of Climate Change; Energy; Environment and Water 2022a) and the modelling has shown that while *Litoria lorica* can be found at higher elevations, it prefers lower elevations such as the areas where it has recently been rediscovered. It is recommended that, in order to help these species, more attention is paid to climate change mitigation and effort put in to stop or reverse the effects of fossil fuel emissions. SSP126 showed that *Litoria lorica* will not fare well with increased climate change and the aim should be to not exceed the global temperature rise set out by the IPCC in SSP126. Known populations should be monitored and assistance given if required but minimal manual searches should be done in order to maintain habitat health.

Litoria nyakalensis is a frog whose distribution has never been well understood and this study has helped to clear up some unknowns. This is a frog who prefers the cooler climates of higher elevations such as those over 600m with a stable climate and little seasonality. While it is recommended that searches be carried out to discover extant populations of this species, manual searches are shown to cause damage and therefore should be undertaken with caution.

Taudactylus acutirostris is a frog known from many sightings but is known to be a highly cryptic species. This species relies on trees, built up areas and grass for habitat and to a lesser degree water and crops. The modelling shows future populations could benefit from a minor increase in global temperatures due to climate change although any large change could be catastrophic. Therefore it is recommended that climate change should be avoided as much as possible.

Taudactylus rheophilus was thought to be the species that would suffer the most from climate change (WTMA 2015) but the future climate modelling shows that this is not the case with both *Litoria lorica* and *Litoria nyakalensis* faring worse. The *Taudactylus* frogs appear to thrive with a small increase in temperature but struggle with the conditions of climate change in 2080. This is also the only frog that saw an increase in the amount of highly suitable habitat with the exclusion of elevation. *Taudactylus rheophilus* is the frog shown to benefit the most from minor increases in temperature.

The results of the future climate modelling show the distributions of all four frog species are going to face severe declines resulting in no suitable habitat by the year 2080 with severe declines by 2040. The land use these frogs are most likely to be found on is nature conservation, showing that the natural protected areas of the Wet Tropics are vital to these species. The main land cover type on which these species of frogs live is trees, tied with grass and shrub/scrub third.

Surprisingly some built up areas were shown to be suitable area for *Taudactylus acutirostris* while irrigated land was suitable habitat for *Litoria nyakalensis*. The most important environmental variable for *Litoria lorica* was slope while temperature seasonality was the most important climatic variable. *Litoria nyakalensis* is reliant on temperature seasonality and land use. *Taudactylus acutirostris* requires elevation and land use while *Taudactylus rheophilus* is most impacted by temperatures and temperature seasonality. This species likes warmer temperatures and does not favour temperate seasonality.

Some preconceptions held about some of the species have been contradicted. There is no restriction to the higher elevations for *Taudactylus rheophilus* or *Litoria lorica*. The habitat of *Taudactylus acutirostris* is not as similar as has been proposed in past literature to *Taudactylus rheophilus* and assumptions about unknown breeding requirements and life history should be questioned. Updated knowledge of these species should be utilised to provide these species the best protection.

For future studies, the suggested surveys should not be limited to what is thought to be the most optimal environment for a species as the majority of rediscoveries that have occurred worldwide to date have been in habitat thought to be marginal or unsuitable. *Litoria nyakalensis* requires searches to the western edge of the Wet Tropics since most historic searches appear to have focused on the more coastal areas. *Taudactylus acutirostris* and *Litoria lorica* are more likely to be found above latitude -16.75° while latitude is not an issue for *Litoria nyakalensis* or *Taudactylus rheophilus.* There is a chance these species are still extant with as of yet undiscovered populations in areas highlighted in this study. There is not enough evidence to propose a change from critically endangered to extinct without searches of these areas. The major threats have been identified as climate change and chytridiomycosis and while these frogs will not start to decline significantly from climate change until after 2040, there is still significant reason to act now.

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