Conserving amphibian and reptile diversity in north Madagascar:
Contributions from baseline herpetological survey work

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ABSTRACT

Madagascar has long been recognized as one of the world's priority global hotspots for biodiversity conservation. Its herpetofauna, in particular, is extremely species-rich and diverse with high levels of endemism. By far the most important threat to its continued survival is the relentless destruction of its primary habitats. Socioeconomic factors in combination with particular aspects of Malagasy culture have led to the exploitation of natural resources which have already had an impact at a national level. Conservation strategies are in place to protect this unique fauna. However, in practice they are constrained in part by a lack of information regarding the distribution, abundance, natural history, and habitat requirements of threatened species. Accessible information, generated by baseline herpetological surveys, is particularly lacking for several key regions such as the northern province of Antsiranana. The first study in this research programme represents a review of modern herpetological survey work (1994-2007) in Madagascar and serves to highlight why Antsiranana was selected as a region of focus. The following three studies are focused on baseline herpetological survey work that was conducted in several key sites of conservation importance throughout the province. A further three studies provide an account of six species (previously unknown to science) that were discovered and described as a result of this survey work. The remaining two studies provide an insight into the impact that anthropogenic habitat alteration is having on lizard abundance, diversity and community composition in the extreme north of this island. Overall, these studies represent an advancement of the knowledge regarding a threatened herpetofauna. They elucidate a number of issues pertaining to broader questions of conservation biology in Madagascar that have been traditionally confounded by a lack of evidence.

"In the end, our society will be defined not only by what we create, but by what we refuse to destroy"

John C. Sawhill (1936-2000), president, The Nature Conservancy, 1990-2000

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In particular, I am extremely grateful to the late Dr. Peter Stafford. It was under his guidance and tutelage that I was able to secure my first experience of biological research in the field and ascertained how to overcome the various hurdles required to publish the results in a peer reviewed format. It was also with his encouragement and by his recommendation that I was able to pursue this PhD on the basis of published works. His friendship remains sorely missed.

The majority of studies on which this programme of research is based were conducted during my time as Research Coordinator for the volunteer based NGO Frontier. Although funding and resources were often somewhat lacking the same could never be said for the field staff. Consequently, I would like to extend my personal thanks to Mr. Jeremy Sable, Mr. Steven Megson, Ms. Janine Robinson, Mr. Jeffrey Dawson, Ms. Katie Green, Mr. Charlie Gardner, Mr. Philip Cowling, Ms. Natasha Calderwood and of course Puppy (quite possibly the most obese and loyal dog on the island). Their companionship on many a long forest hike will always be fondly remembered and greatly appreciated.

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Upon my return to the UK I found myself in possession of a lot of data but not nearly as much of a clue on how to go about utilizing it. Fortunately, many distinguished experts in their field were quick to offer me a helping hand. Therefore I would also like to extend my personal thanks to Dr. Frank Glaw, Dr. Jorn Köhler, Dr. Michael Franzen, Dr. Zoltan Nagy, Prof. Miguel Vences, Dr. Raymond Saumure, Prof. Malcolm McCallum, Mr. David Emmet, Dr. Sunil Kumar and of course Dr. Stewart Thompson. Their unending support, selfless encouragement and guidance have been invaluable during this time.

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CONTENTS

CHAPTER 1: INTRODUCTION

The herpetofauna of Madagascar

The island of Madagascar (the fourth largest island in the world) has a surface area of 587,000 km^2, and exhibits substantial environmental gradients, with diverse climates and complex topography (Raxworthy *et al.,* 2008). This, together with the Gondwanan origin and long isolation (88 Myr bp) of this island (Storey *et al.*, 1995; Raxworthy *et al.,* 2008) has resulted, for many biological groups, in the evolution of species-rich clades that exhibit species-level regional endemism (Glaw and Vences, 2007). Consequently the biota of Madagascar has long been recognized as one of the world's priority global hotspots for biodiversity conservation (Myers *et al.,* 2000). The herpetofauna of Madagascar in particular is extremely species-rich and diverse with high levels of endemism (Glaw and Vences, 2007).

The amphibian fauna of Madagascar is highly exceptional and 100% of the native species are endemic to the island (Glaw and Vences, 2007). The native fauna comprises 5 endemic evolutionary lineages of frogs, two of which (the mantellids and the microhylids) are especially species-rich (Glaw and Vences, 2007). Furthermore, in an analysis conducted by Glaw and Vences (2003), 22% of the Malagasy frog species described at the time were identified as potential regional endemics. Although further research may reveal that some of these species are actually more widespread than is currently known, it seems that in many cases, very narrow ranges are a biological reality for certain taxa (Glaw and Vences, 2007). Currently around 244 Malagasy amphibian species have been described (Vieites *et al.,* 2009), but many others (approx. 150) remain to be formally named despite having been identified (Glaw and Vences, 2007). Consequently it is currently thought that a total of more than 400 amphibian species (about 3.8% of the world's amphibian fauna) are restricted to Madagascar (Vieites *et al.*, 2009).

Similarly, the non-marine reptile fauna of Madagascar is also characterised by a high level of endemism (recently estimated at 92% of known species [Glaw and Vences, 2007]). However, (in contrast to amphibians) there are a number of species that are conspecific with populations from the African mainland (e.g. *Crocodylus niloticus*), and several species that occur on the Comoro islands (e.g. *Phelsuma dubia*) (Glaw and Vences, 2007). This is probably in part because reptiles are more suitably adapted for transoceanic dispersal (Raxworthy *et al.,* 2002). Compared to amphibians, there are many more reptile lineages in Madagascar – currently at least 21 extant non marine lineages have been distinguished (Glaw and Vences, 2007) – and their phylogenetic relationships and ages of origin are in general less comprehensively known (Raxworthy, 2003). Based on current taxonomy, the distribution areas of many single reptile species appear to be larger than that of amphibians, but this pattern remains to be studied in more detail (Glaw and Vences, 2007). To date, a total of 363 species of reptile have been described from Madagascar (Glaw and Vences, 2007).

Under threat

The current situation with regards to the herpetofaunal diversity of Madagascar is incongruous. The recent level of discovery of previously unknown species is higher than during any period of scientific exploration of the island (Vieites *et al.,* 2009). In fact these taxa are being found at a rate greater than at which they can be described (Glaw and Vences, 2007). Unfortunately, at the same time, the threat to the islands herpetofauna and to its biological diversity in general has never been more dire than it is today (Glaw and Vences, 2007).

Globally, amphibian populations are in decline and their associated extinctions are a well-publicized phenomenon (Stuart *et al.,* 2004). Consequently this vertebrate group has garnered a central place in the concern of biodiversity loss amongst both biologists (Alford and Richards, 1999) and the general public (Phillips, 1994). It has also been demonstrated that many reptile populations are experiencing declines of a similar magnitude (Gibbons *et al.,* 2000; Huey *et al.,* 2010). Several factors have been identified and are globally considered as the main potential threats (international trade, environmental pollution, subsistence hunting, large scale changes in agricultural practice, chytridiomycosis, climate change, habitat fragmentation and habitat loss) (Glaw and Vences, 2007). However, despite these threats, it appears that to date there have been no known amphibian species extinctions in Madagascar (Andreone *et al.,* 2005).

By far the most important threat to all or nearly all Malagasy herpetofauna and most other endemic biota of the island is the continuing destruction of primary habitats, especially those of the eastern rain forests where most amphibian species occur (Glaw and Vences, 2007). Socioeconomic factors such as rapid population growth, poor education and other particular aspects of Malagasy culture are partly responsible for obliging local residents to employ harmful agricultural methods and other activities that lead to the exploitation of natural resources (Durbin *et al.,* 2003)

These pressures on natural resources have already had a major impact at a national level, for example Myers *et al.,* (2000) estimated that more than 90% of the original natural vegetation has already been lost in Madagascar. Continued forest clearance will lead to the eventual fragmentation of the remaining areas of forest (with serious consequences on herpetofauna [e.g. Vallan, 2000]). Although as yet no catastrophic declines or extinctions have been detected, given the current rates of habitat loss and degradation this seems inevitable (Irwin *et al.*, 2010).

Consequently, due to these high levels of habitat destruction and predicted extinctions (Myers, 1988; Myers *et al.,* 2000; Brooks *et al.,* 2002), the herpetofauna of Madagascar is also recognized as one of the world's priority global hotspots for biodiversity conservation as it is characterized by a relatively high number of threatened species. Andreone *et al.* (2005) reviewed the extinction risk for all species of Malagasy frogs in the context of the Global Amphibian Assessment (by evaluating their distribution, occurrence in protected areas, population trends, habitat quality, and demand for the commercial pet trade). Of the 220 described species that were evaluated at the time, nine were classified in the category of highest risk, Critically Endangered. Of the remaining species, 21 were categorized as Endangered and 25 as Vulnerable. So far no such in depth analysis has been carried out for the reptiles of Madagascar (Glaw and Vences, 2007). However, currently four species are classified as Critically Endangered, two are categorized as Endangered and eight as Vulnerable (IUCN 2009).

The current lack of baseline data

Conservation strategies are in place to protect this unique biodiversity, including the identification of priority areas in Madagascar for threatened or overall species diversity and their inclusion in protected nature reserves (Ganzhorn *et al.*, 1997; ANGAP, 2001). In theory, these protected nature reserves are an effective means to protect tropical biodiversity (Bruner *et al.*, 2001) and they can be successful at stopping land clearing, and to a lesser degree effective at mitigating logging, hunting, fire, and grazing (Bruner *et al.*, 2001).

However, in practice the identification and protection of priority areas globally is constrained by a lack of information regarding the distribution, abundance, natural history, and habitat requirements of threatened species and the size, condition, and threats to survival of forest remnants (Smith *et al.*, 1997). This type of baseline in-formation is needed to integrate information relevant to existing conservation and development programmes and guide the course of future management strategies (Kremen *et al.*, 1994; Balmford and Gaston, 1999; Andreone *et al.*, 2008a; Kremen *et al.*, 2008).

Consequently, decisions affecting herpetofaunal biodiversity often have to be taken without all the necessary information – data may be unavailable, incomplete, or unreliable (Funk and Richardson, 2002). This is partly because many surveys, in Madagascar and elsewhere, are conducted over a fairly short period of time, and often within sites that are already been designated as protected areas (e.g. Bildstein, 1998).

It is widely accepted that there are major financial, labour, and time-related constraints associated with conducting such work (Bildstein, 1998).

Despite these constraints, there have been large increases in the amount of information available on the Malagasy herpetofauna over the last 18 years (Andreone *et al.,* 2005). Large-scale taxonomic inventories conducted since 1991 have explored new areas and applied more efficient techniques (e.g. standardized call surveys, visual encounter surveys and DNA bar-coding for identification) (Vences *et al.,* 2008a). However, much of the published data cannot be directly compared as it has been collected by numerous different researchers using varying taxonomic concepts and interpretations (Glaw and Vences, 2007). This problem is further exacerbated by the fact that traditionally many authors have failed to provide all of the necessary data required for voucher specimens, e.g. exact GPS coordinates in order to confirm locality and certain taxonomic data (e.g. DNA samples, coloration in life, advertisement calls) required to differentiate between morphologically similar species (Glaw and Vences, 2007).

Aims and plan of this thesis

This thesis is concerned with the herpetofauna found within the Antsiranana province of northern Madagascar. The series of studies upon which it is based were conducted over a period of some six years (2005-2010) and represent an outgrowth of my continuing research and interest in the herpetofauna of the island. Its overall objective is to summarize the main results of these studies in terms of their broader significance, identify general patterns, and draw inferences on particular aspects of the research where data have otherwise been lacking. The results are compared with other studies, especially where these are contradictory or suggest the possibility of other hypotheses. Potential avenues for further research are also examined.

In this first chapter a general overview of the herpetofauna of Madagascar has already been provided serving to highlight: (1) the significance of this unique fauna; (2) the current threats which they face; and (3) the current lack of baseline data which is so desperately needed to conserve them. In addition, it also provides an outline summary of the different component aspects of the research.

Chapter 2 is focused on the highlighting the significance of baseline herpetological surveys. Specifically it aims to: (1) provide a brief historical overview of such field studies in Madagascar; (2) demonstrate how modern surveys fit into the context of this research; (3) identify key criteria that should be met to ensure that future herpetological research initiatives are kept relevant and verifiable; and (4) suggest potential solutions to limiting factors which might be inhibiting such work.

Chapter 3 focuses on a series of baseline herpetological surveys which were conducted by the author as part of this research. It includes: (1) a general overview of the Antsiranana province and rationale for its selection as area of focus; (2) a brief account of the findings for each of our survey sites (highlighting the contribution that has been made to the existing literature); and (3) a summary that draws some inferences with regards to general patterns of biodiversity within this northern most province.

Chapter 4 provides an account of 6 species (previously unknown to science) that were discovered and described as a result of this research. Specifically it aims to: (1) highlight the significance of new species with regards to conservation efforts in Madagascar; (2) provide an overview of the current taxonomic status for each species; (3) identify key morphological and molecular characters which distinguish them from other known species; and (4) clarify the current conservation status of each species based on existing data.

Chapter 5 is focused on the impact that anthropogenic habitat alteration is having on the unique herpetofauna found in the extreme north of this island. It attempts to provide: (1) a list of the different detrimental anthropogenic activities that were observed during this research; (2) a summary of the different factors that can affect the impact of habitat alteration and loss; (3) a brief review of the habitat loss focused research that has been conducted in Madagascar to date; and (4) a summary of our findings with specific regards to the impact of clear cutting and orchard cultivation on the abundance, diversity and community composition of lizard species.

The thesis concludes with Chapter 6, an overall summary of the work, including its limitations, potential for future development and future recommendations for the conservation of Malagasy herpetofauna.

CHAPTER 2: HERPETOLOGICAL SURVEYS IN MADAGASCAR

Significance and trends

Inventories of Madagascar's herpetofauna are a major prerequisite for any efficient conservation strategy focused on these organisms (Vallan, 2000; Andreone *et al.*, 2005; Vences *et al.*, 2008a; D'Cruze *et al.*, 2009a). Furthermore, they are the only means to obtain more complete information on the distribution and biogeography of these organisms and are also the main driver responsible for the discovery of new species (Glaw and Vences, 2007; Vences *et al.*, 2008a,b; D'Cruze *et al.*, 2009a). Given the significance and current lack of baseline data in Madagascar a new herpetological survey programme was initiated to help address this situation. This programme resulted in several peer reviewed publications to which this thesis pertains.

To begin, a literature review was carried out focused on herpetological surveys published for Madagascar (referred to hereafter as "the survey literature review") (D'Cruze *et al.*, 2009a). Specifically, this aspect of the research programme characterized the type of herpetological survey work which had been conducted over a 14 year period (1994-2007) by focusing on manuscripts that included a detailed species inventory or list. It was hoped that this process would detect general trends, identify any biases, limiting factors, and facilitate the provision of recommendations that would help guide the design and site selection of future field research. Vitally, it would also help ensure the effective allocation of the limited resources currently available and avoid the unnecessary duplication of effort.

Traditionally, historical analyses of herpetological research in Madagascar used the number of species descriptions per decade as an indicator for research intensity (e.g. Glaw and Vences, 1994; 2000) (Vences *et al.,* 2008b). These works detected an unprecedented rise in research intensity since the 1990s, with more amphibian and reptile species described from 1990-1999 than any decade before (Glaw and Vences, 2000; Vences *et al.,* 2008b). Similarly, a prior analysis of a list of almost 1400 publications focused on Malagasy amphibians and reptiles revealed a clear trend of increasing research intensity from the year 1838 until the present day (with maximum levels reached for the periods of 1990–1999 and 2000–2009 [Vences *et al.,* 2008b]). In contrast, the survey literature review concluded that the number of published manuscripts focused on herpetological survey work appears to have remained relatively constant during the period 1994–2007 (D'Cruze *et al.,* 2009a).

Initially, one might assume that a similar marked increase in this particular type of scientific research has not occurred as it is not required. For example, it may be that already there is sufficient information available in the existing literature (detailing the composition, geographical, ecological, and seasonal distribution of the herpetofauna in Madagascar) and that the majority of published surveys are monitoring efforts conducted to observe changes in population dynamics or community structure. However, unfortunately this is not the case (Vences *et al.,* 2008b) and it is clear that the existing data currently available as a result of herpetological survey work is far from comprehensive (D'Cruze *et al.,* 2009a). It is estimated that, at its current rate, it will take approximately another 20 years before even a preliminary herpetological species list is accessible and available for all of the current protected areas in Madagascar (Glaw and Vences 2007; D'Cruze *et al.,* 2009a).

The survey literature review also highlighted that the field work conducted to date has not been equally distributed throughout Madagascar with regards to either the protective status of study areas or habitat type (D'Cruze *et al.*, 2009a). It was found that; (1) the majority of published survey work has been conducted in protected areas; and (2) the areas characterized by humid rainforest (predominantly located in the east of the island) have attracted most of the attention from researchers (probably because of their high biodiversity and perceived advanced conservation needs) (D'Cruze *et al.*, 2009a). This information was taken into account when selecting a suitable study area and specific survey sites as part of the new research programme. Consequently, field work covered sites within both protected and non protected areas and also included habitat types that have been traditionally overlooked by researchers (e.g. primary western dry forest and primary coastal forest).

Ensuring relevance and verifiability

Traditionally, amphibian surveys are carried out in a combination with surveys of the reptile fauna (Veith *et al.*, 2004) as survey techniques used to target either taxa typically result in the capture of species belonging to both of these vertebrate groups (Raxworthy, 1988; D'Cruze *et al.*, 2009a). The results of both taxa are presented in the form of species lists per site (e.g., Andreone *et al.*, 2003; Nussbaum *et al.*, 1999; Rakotomalala, 2002; Vences *et al.*, 2002). The survey literature review found that the majority of survey-based manuscripts published over the last 14 years (86%) provide information for both reptiles and amphibians (D'Cruze *et. al.*, 2009a).

However, the existence of multiple sibling species of difficult morphological identification (which is especially true for amphibians [e.g., Glaw *et al.*, 2001a; Köhler *et al.*, 2005]) and the fast taxonomic progress in understanding the species diversity of this fauna (Blommers-Schlösser and Blanc, 1991; Glaw and Vences, 2000, 2003, 2006) casts doubts on the efficiency and significance of the common survey practice in Madagascar (Vences *et al.*, 2008a). Consequently it is vital that researchers strive to ensure that the right combination of detection and identification techniques are selected and implemented (adhering to precise recommendations), for an appropriate duration of time, in order to fully ensure data verifiability (Vences *et al.*, 2008a).

With regards to species detection, a wide range of sampling methodology was used during the new research programme in order to gauge the diversity of the full complement of species at each of our selected survey sites. The main survey techniques used were: (1) pitfall trapping with drift fences; (2) visual encounter surveys; (3) searching for calling frogs; (4) refuge examination; and (5) opportunistic searching. A concerted effort was also made to glean information about finding amphibians and reptiles from local people living in the area. It is generally accepted that these traditional methods will suffice given that they are carried out over longer periods (i.e. a week or more) (Vences *et al.*, 2008a). Therefore some of the less traditional detection techniques advocated by some researchers e.g. tadpole surveys were not utilized (Vences *et al.*, 2008a).

With regards to identification, the research programme strived to ensure the systematic collection of data that were as informative and reliable as possible. This included the collation of digital photos, morphological data, associated ecological data, geographical coordinates of localities using a global positioning receiver (GPS) and call recordings (when possible). All species lists were accompanied by a list of voucher specimens which we deposited in open-access public collections and all species were cross verified by specialized researchers with extensive morphological experience (via specimens or photographic records). Furthermore tissue samples were collected (clearly assignable to individual specimens) and standardized gene fragments were sequenced to aid the identification of morphologically cryptic taxa.

Personnel

It is widely accepted that there are major financial, labour, and time-related constraints associated with conducting field work such as herpetological surveys (Bildstein, 1998). In order to address these limitations the participation of non-specialist, self-funded volunteer researchers (hereafter referred to as volunteers) was fostered throughout the survey focused field work components of the research programme. The use of volunteers in scientific research has been criticized mainly due to the fact that they are considered unreliable as they lack a high level of biological knowledge and training (Bildstein, 1998). However, volunteers have increasingly viewed as a viable option by host countries with financial, labour, or training constraints (Mumby *et al.,* 1995) which is apparent from their increasing contribution to conservation biology and wildlife management over the past 20 years (e.g. Bildstein, 1998; Fore *et al.,* 2001; Foster-Smith and Evans, 2003; Gill, 1994; Newman *et al.,* 2003).

Where possible the participation of numerous Malagasy university students was also fostered. For a long time the participation of Malagasy researchers in the exploration work and publications of Madagascar's flora and fauna has remained marginal, largely reflecting colonial history (Vences *et al.,* 2008b). Although it has now been recognized Malagasy scientists can (and have in recent decades) strongly contribute to advancing the knowledge on Madagascar's biota (there is an increasing trend in the participation of Malagasy researchers in the process of publishing research results [Vences *et al.,* 2008b]).

The survey literature review indicated that, to date, volunteers and Malagasy researchers have been under-utilized in Madagascar. It seems that both of these groups should be viewed as key collaborators that have the potential to help in addressing the financial, labour, and time-related constraints associated with conducting modern herpetological survey work.

CHAPTER 3: SURVEYS CONDUCTED AS PART OF THIS RESEARCH

The herpetofauna of the Antsiranana province

The Antsiranana Province (with an area of 43,406 km^2) is one of the six autonomous provinces traditionally used to subdivide the island (Figure 1). It is located in the extreme north of Madagascar. Part of the sub-humid bioclimatic zone originally defined by Cornet (1974) and further utilized by Schatz (2000), the area is generally subject to marked seasonal variation, with a distinct and relatively long dry season followed by a wet season lasting from December to April (Jury, 2003). The altitude of this province ranges between 0 and 1,475 m.a.s.l. and is characterized by a variety of different habitat types including dry deciduous forest, limestone karst, coastal forest, low altitude rainforest, high altitude rainforest and anthropogenically altered areas (Raxworthy and Nussbaum, 1994; D'Cruze *et al.,* 2007; D'Cruze *et al.,* 2008; Megson *et al.,* 2009).

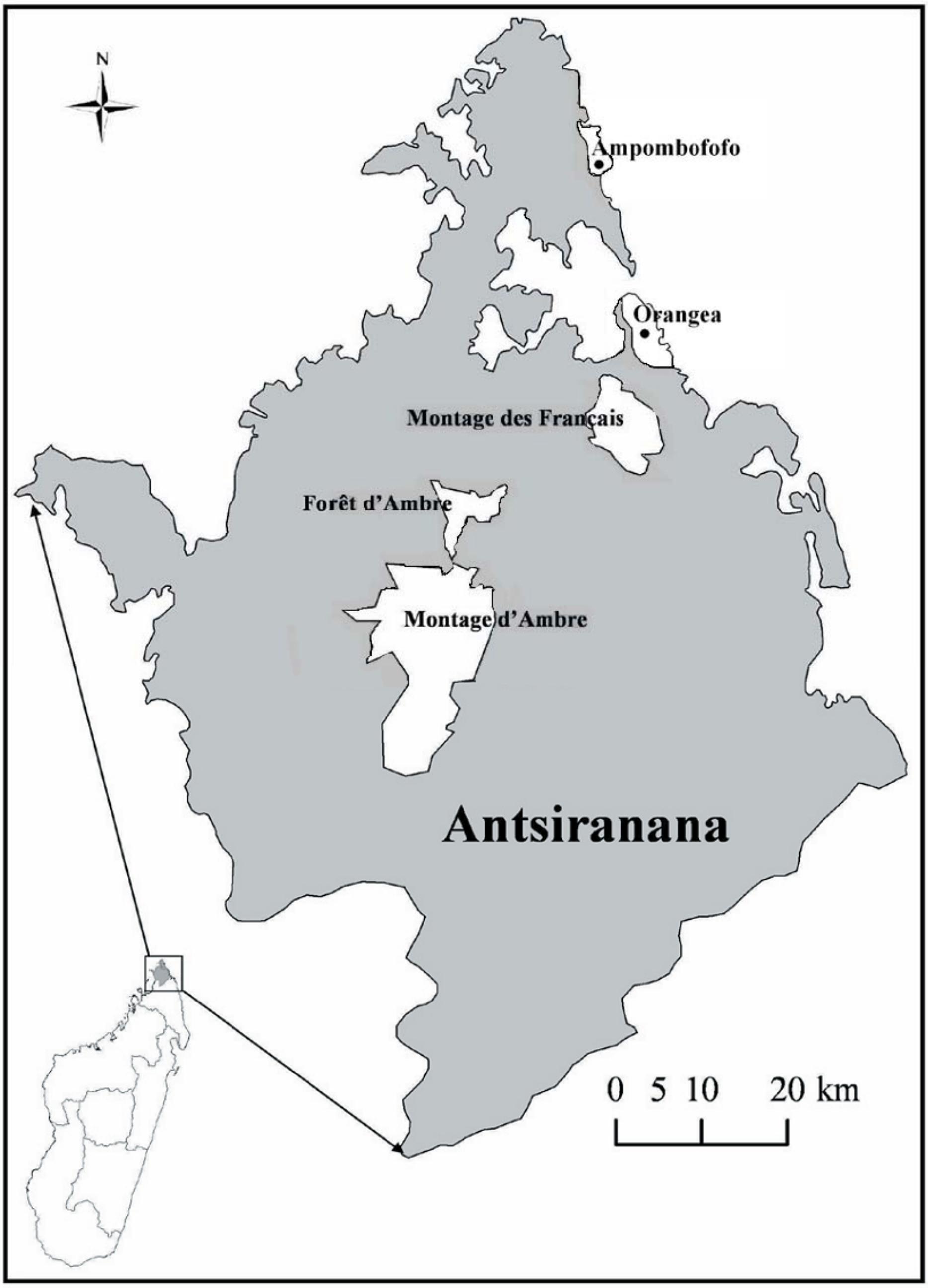

Figure 1: Map of study area in Northern Madagascar

There were several reasons why sites were selected in the extreme north of this particular province for the new herpetological research program. Firstly, fieldwork conducted in recent years had already begun to reveal the importance of this area as a biological centre of herpetological diversity and endemism (D'Cruze *et al.,* 2007). This has included the discovery of a number of undescribed herpetological taxa (e.g. Pintak and Böhme, 1988; Raxworthy and Nussbaum, 1994; Glaw *et al.,* 2001b; Mori *et al.,* 2006; Rakotondravony, 2006) and significant geographic range extensions (e.g. Raxworthy and Nussbaum, 1994; Rakotondravony, 2006). Furthermore, this province also falls within the north Bemarivo centre of endemism (one of 12 areas of endemism identified throughout the island according to the main watersheds and species distribution data [Wilmé *et al.,* 2006]).

Secondly, an initial survey literature review (conducted as part of this research programme) revealed that comparatively little fieldwork had been conducted in this particular province and that essential baseline data was lacking (D'Cruze *et al.,* 2009a). Currently, the unique herpetofauna found in the extreme north of this province is conserved by a network of protected areas consisting of Montagne D'Ambre National Park, Forêt d'Ambre Special Reserve, Lokobe Special Reserve, Analamera Special Reserve, Ankarana Special Reserve and Montagne des Français (recently awarded temporary protected status). Prior to the survey work, conducted as part of this new research programme, only two of these six biological refuges (Montagne D'Ambre National Park [Raxworthy and Nussbaum, 1994] and Lokobe Special Reserve (Andreone *et al*., 2003]) had been recently subjected to intensive herpetological survey work resulting in a peer reviewed scientific publication. However, more recently, a detailed species list was published for the Tsarakibany area (an unprotected and fragmented patch dry deciduous forest located between Montagne d'Ambre National Park and Ankarana Special Reserve) (Durkin *et al.*, 2011).

Thirdly, Antsiranana is characterized by a range of different habitat types, many of which have been traditionally neglected by researchers leading herpetological surveys. For example, the survey literature review (D'Cruze *et al.,* 2009a) supported prior claims that there have been lower conservation efforts in the dry deciduous forests of Madagascar (common throughout the province) when compared to those undertaken in Madagascar's evergreen rainforest (Ganzhorn *et al.,* 2001). Furthermore, the province is also characterized by several unprotected areas (e.g. Montagne des Français) that on initial analysis appeared to be a potential site of herpetological importance (Glaw *et al.,* 2001b). It was hoped that new survey work conducted in these areas would allow for the identification of new priority areas and provide the evidence required to advocate for their inclusion as protected nature reserves.

Key sites of herpetological importance

Specifically, the new herpetological research programme concentrated on a number of different survey sites (all of which are located within one of four key sites of herpetological importance): (1) The Montagne d'Ambre mountain complex; (2) Montagne des Français Massif (3) Ampombofofo; and (4) Orangea. The main findings for each of these key sites and their significance are summarized briefly below:

The Montagne d'Ambre mountain complex

The Montagne d'Ambre mountain complex runs north – south at the extreme northern tip of Madagascar. The herpetofauna of this complex is currently protected by two IUCN Category II protected areas both of which were formally created in 1958. The Forêt d'Ambre Special Reserve (4,810 ha) includes low-mid altitude rain forest between 150 and 1,143 m.a.s.l. The adjacent Montagne d'Ambre National Park (18,200 ha) also offers protection to the high altitude rain forest between 850 and 1,475 m.a.s.l. Both the Forêt d'Ambre Special Reserve and the Montagne d'Ambre National Park are currently managed by SAPM (System of Protected Areas of Madagascar) formerly known as ANGAP ('Association Nationale pour la Gestion des Aires Protégées').

A total of 20 amphibian and 39 reptile species were encountered in the first published survey to focus on the Forêt d'Ambre Special Reserve. Consequently, most of these species were new records for the area (D'Cruze *et al.*, 2008). This research considered three of these species as locally endemic to Forêt d'Ambre (*Boophis baetkei*, *Brookesia* sp. nov., and *Rhombophryne matavy*) and an additional 22 species as potential regional endemics (according to information available at the time). Consequently they should be considered among the most vulnerable elements of the herpetofauna of this area. Several species encountered during the survey required special mention as their occurrence in the Forêt d'Ambre significantly contributed to the current information regarding their distribution in Madagascar (*Mantella viridis*, *Thamnosophis martae* and *Uroplatus giganteus*).

In contrast to the Forêt d'Ambre Special Reserve, the herpetofauna of Montagne d'Ambre National Park has been surveyed intensively by different researchers since long (Mocquard, 1895; Ramanantsoa, 1974; Andreone, 1991; Glaw and Vences, 1994, 2007; Raxworthy and Nussbaum, 1994). It is therefore remarkable that the new survey work discovered several species previously unknown from this site (*Boophis tephraeomystax*, *Mantidactylus* aff. *betsileanus*, *Furcifer* sp. nov., *Paroedura* cf. *gracilis*, *Amphiglossus mandokava*, and *Stenophis granuliceps*). Consequently an updated species list (composed of 24 amphibians and 51 reptiles) was provided for this particular protected area (D'Cruze *et al.*, 2008). Analysis found that 24% of these species appear to be restricted to the high altitude rainforest found above 900 m elevation. The research also concluded that two species that appear to be locally endemic to Montagne d'Ambre (*Stumpffia* sp. 1 and *Furcifer* sp. nov) and an additional 36 species appear to be regional endemics (according to information available at the time). Consequently these species should be considered among the most vulnerable elements of the herpetofauna of this area.

A small privately owned and managed area of forest known as the 'Fontenay Nature Park' which borders both of these protected areas (D'Cruze *et al.*, 2008) was also surveyed. Survey efforts did not result in the capture of any species that were not already known from either the Forêt d'Ambre Special Reserve or the Montagne d'Ambre National Park. However this portion of the research programme provided the opportunity produce a preliminary species list of 36 species list for this area and additional information regarding the altitudinal distribution of the herpetofauna found within the Montagne d'Ambre mountain complex.

Montagne des Français

Montagne des Français is one of the calcareous massifs (known locally as "tsingy") located in the extreme north of Madagascar. The altitude of this massif ranges between 100 and 400 m and is characterized by a mosaic of caves, canyons, and corridors. The vegetation of Montagne des Français is of a distinctly more mesic type than that of its surroundings, and has been described as transitional between mid-altitude rainforest and dry deciduous western forest (Ramanamanjato *et al.,* 1999). Until recently the Montagne des Français massif received no formal protection. However, in late 2006, it was nominated as a Durban Vision Potential Site requiring some form of protection (Ministère de l'Environment, des Eaux et Forets, 2005) and granted Temporary Protected Area Status.

Montagne des Français was initially surveyed in 2005 for a period of approximately 1 year. During this time nine amphibian and 52 reptile species were recorded in the first detailed survey to focus on this area (81% of the species found were new records for the area) (D'Cruze *et al.,* 2007). It is therefore of note that in 2008 (during a second relatively brief survey) an additional six species that were not previously known from this site were discovered. It is now known that in total the Massif is home to at least 12 amphibians and 55 reptiles. Analysis found that the majority of species are only found in relatively undisturbed areas of forest with diversity peaking at 100-200 m elevation. Research concluded that the five species (*Amphiglossus* sp. nov., *Madagascarophis* sp. nov., *Paroedura* sp., *Paroedura lohatsara* and *Stumpffia* sp. 3.) considered to be locally endemic to the Massif (according to current information) are among the most vulnerable elements of this herpetofauna.

Bobaomby and Orangea

A significant proportion of our research program (over a period of approximately 1 year) was conducted in an area known as Ampombofofo in the Bobaomby region of the island. Ampombofofo is located approximately 20 km north of the town of Antsiranana (Diego Suarez), the administrative capital of the Antsiranana province. Its close proximity to the coast and the sandstone geology has resulted in a unique habitat matrix composed of large patches of primary western dry forest fringed by primary coastal forest (Megson *et al.*, 2009). In addition, anthropogenically disturbed areas of habitat are also present throughout this region (Megson *et al.*, 2009). Therefore a smaller team was deployed to conduct a short period of fieldwork in an area of coastal scrub forest located within the area known as Orangea. Both of these areas were selected as part of this research programme in order to include previously undocumented sites located outside of the existing protected area system in the extreme north of Madagascar.

A total of nine amphibian and 46 reptile species were encountered in Ampombofofo in the first survey to be conducted at this locality (Megson *et al.*, 2009). All of the species discovered in this survey are new records for the area. It is important to note that for all of these species this locality data represent the northernmost limit of their known range (Megson *et al.*, 2009). Many species encountered during this study also require special mention as their occurrence in Ampombofofo significantly contributes to the current information regarding their distribution in Madagascar (*Mantella viridis*, *Liophidium therezieni* and *Amphiglossus ardouini*). Research suggests that 21 of these species (38%) appear to be regional endemics restricted to only a few places in north Madagascar (according to existing information) and should be considered among the most vulnerable elements of the herpetofaunal community of this area. In addition a total of three amphibian and 22 reptile species in were recorded in Orangea. It appears that six of these species (24%) should be considered as regional endemic with distributions restricted to the extreme north of Madagascar.

Relevance to patterns of biodiversity

Natural biogeographical processes are believed to be largely responsible for the current distribution of amphibians and reptiles in Madagascar (Wilmé *et al.,* 2006). For example volcanic activity (Du Puy and Moat, 1996) is believed to be responsible for the formation of the Montagne d'Ambre mountain complex and its current isolation from the other northern and eastern forest blocks (Raxworthy and Nussbaum, 1994). Due to this isolation, the humid rainforest of this complex may have served as a biological refuge. Therefore it may have preserved relict populations of species that disappeared from other regions of the eastern rainforest belt during dry periods; or it may have facilitated speciation through geographic isolation (Raxworthy and Nussbaum, 1994). Both of these factors would have produced endemics and therefore this complex may contain species that are found nowhere else (Köhler *et al.,* 2008).

However, it is important to note that the disruptive anthropogenic activity that followed human settlement (estimated at approximately 1,500 - 2,000 years ago [Hurles *et al.,* 2005]) and subsequent anthropogenic deforestation (Vallan, 2000, 2002; D'Cruze *et al.*, 2006) is also believed to have played a pivotal role in shaping patterns of distribution (Vallan, 2003). For example it has been suggested that prior to human invasion continuous lowland corridors of dry or transitional forest linked the lower slopes of the five major massifs of Analamera, Ankarana, Daraina, Montagne D'Ambre and Montagne des Français located in the north (the current distribution of the skink *Trachylepis tavaratra* at all of these locations has been used as evidence to support this hypothesis [Ramanamanjato *et al.*, 1999]).

The findings of this new research program have resulted in patterns of distribution similar to that of *Trachylepis tavaratra* for a significant number of other robust species and add further weight to the hypothesis. For example following an extensive herpetological survey, Montagne des Français was identified as an important biological centre of herpetological endemism. It remains true that several species (morphologically adapted to the calcareous formations found within e.g. *Stumpffia* sp. 3) still appear to be restricted to this Massif. However, the results of our subsequent surveys in surrounding, unconnected areas such as Bobaomby have now demonstrated that many of the species originally identified as locally endemic are also present outside of this massif and are in fact regionally endemic to the north of Madagascar. Examples include *Heteroliodon fohy* and *Liophidium therezieni* that have been recorded from within the area known as Ampombofofo (Megson *et al.,* 2009; Franzen *et al.,* 2009).

CHAPTER 4: DESCRIPTION OF NEW TAXA

New species and their significance

A species becomes known in the formal sense when a Latin binomial (two names consisting of generic and specific epithets) and description are published in the scientific literature, according to the standard rules of zoological nomenclature (ITZN 1999). It is also usually a requirement, at least if published in a mainstream scientific journal, that such descriptions are subjected to a process of critical peer review, there being no legal framework in place by which the rules of the code can be enforced (only by the consensus of biologists to accept them; Jeffrey, 1989).

New species of amphibians and reptiles continue to be described from Madagascar with regular frequency (for example approximately 150 amphibians alone have already been identified but still remain to be formally named [Glaw and Vences, 2007]). It is likely that many others await discovery. It appears (for amphibians at least) that Madagascar has thus far managed to escape the large-scale recent extinctions which have been reported in many other parts of the world (Andreone *et al.*, 2005). With growing concern over habitat loss, however, there is a real possibility that some will become extinct before they are discovered. Given these circumstances, and the fact that most of the earth's total number of organisms are still undescribed (current estimates vary from less 2% to 30%; Winston, 1999), the process of documenting new species clearly remains an important part of taxonomy.

The herpetological survey work associated with this research programme has resulted in the discovery of a number of different taxa that appear to represent undescribed species new to science (D'Cruze *et al.,* 2007; D'Cruze *et al.,* 2008; Megson *et al.,* 2009). As part of this ongoing research program I am continuing to formally describe these species using a combination of morphological and molecular techniques in collaboration with other research colleagues. Six of these formal descriptions have been included as part of this thesis. The justification and significance of their discovery is summarized below.

The family Microhylidae

Günther, 1859

Narrow-mouthed frogs (the family Microhylidae) occur in most tropical regions of the world and are currently represented by approximately 400 species across 64 genera (Glaw and Vences, 2007). This family is characterized by a high level of morphological diversity (especially of osteological characters) which is demonstrated by the fact that many of these genera include just a few species (22 of which are monotypic) Glaw and Vences, 2007). Although many microhylids are stout bodied in appearance and terrestrial in nature, arboreal species are also known to occur, especially in Papua New Guinea and Madagascar (Glaw and Vences, 2007). A typical feature of many microhylids is their rather short snout, giving them an often very characteristic appearance (Glaw and Vences, 2007).

In Madagascar, the Microhylidae is represented by three subfamilies, the Dyscophinae, Scaphiophryninae and Cophylinae (Blommers-Schlösser and Blanc, 1991; Glaw and Vences, 2007). Relationships among these lineages are not well resolved, but novel molecular data appear to indicate that the Cophylinae and Scaphiophryninae are a monophyletic group endemic to Madagascar, whereas the Dyscophinae represent an evolutionary lineage related to Asian microhylids (Van der Meijden *et al.*, 2007).

The sub-family Cophylinae

Cope, 1889

Cophyline microhylids are currently represented by seven genera with more than 40 described species (Andreone *et al.*, 2005; Wollenberg *et al.*, 2008). Next to the endemic Malagasy–Comoroan family Mantellidae (composed of 12 genera and more than 170 species) they represent the second largest amphibian radiation in Madagascar (Köhler *et al.*, 2008). Many additional candidate cophyline species have already been discovered, but still await their description (Vieites *et al.*, 2009; Wollenberg *et al.*, 2008).

The genus *Rhombophryne*

Boettger, 1880

Until recently the genus *Rhombophryne* was considered to be monotypic (*Rhombophryne testudo*), but molecular analyses have shown that several species formerly assigned to the genus *Plethodontohyla* actually belong to *Rhombophryne* (Andreone *et al.*, 2005), which currently includes eight recognized species. Recently, a considerable proportion of undescribed species diversity in the genus was identified by an integrative approach, including five so-called confirmed candidate species supported by molecular genetics and morphological differences, as well as five unconfirmed candidate species with only molecular data available (Vieites *et al.*, 2009).

Rhombophryne species have no (or at most traces of) webbing, non-expanded fingertips and have a size range between 16-60 mm (Glaw and Vences, 2007). Thus far, members of the genus are considered to be largely restricted to rainforest environments or moist high-altitude habitats of northern Madagascar and are either terrestrial or fossorial in nature (Glaw and Vences, 2007). However, some species are found in Madagascar's east, southeast, and the central high plateau. Recently a possibly undescribed species has been discovered in the dry west (Andreone and Randrianirina, 2008). The majority of species also have rather restricted distributions (Glaw and Vences, 2007), which means that they might be particularly at risk from a conservation perspective.

A new species of *Rhombophryne*

***Rhombophryne matavy* sp. nov.**

Herpetological survey work conducted as part of the new research programme in the rainforest of the Forêt d'Ambre Special Reserve, northern Madagascar, revealed a distinctive fossorial microhylid anuran species of the genus *Rhombophryne*. The new species is characterized by medium size (snout–vent length up to 49 mm in males), a stout body, short legs, and tuberculate skin on dorsal surfaces. It is most similar and closely related to *R. testudo* from the Sambirano region, but differs mainly by the absence of barbels on the lower lip, a different advertisement call, and a pairwise total sequence divergence of 8.5% the mitochondrial 16S RNA gene. This species is considered to be at particular risk from a conservation perspective because it appears to be endemic to a relatively small area of lowland transitional forest heavily altered by human activities. According to the International Union for Conservation of Nature criteria, its threat status is classified as ‘‘Endangered’’ B2a.

The genus *Stumpffia*

Boettger, 1881

The endemic Malagasy genus *Stumpffia* contains small to very small ground-dwelling species (*Stumpffia tridactyla* and *Stumpffia pygmaea* range among the smallest frogs in the world [Glaw and Vences, 2007]). Some miniaturized species are as small as 10 mm in their adult stage, and only two described species are known to reach over 20 mm in snout–vent length (Glaw and Vences, 2007).

Many species show digital reduction, as expressed by their common name “stump-toed frogs”. Species of this genus are further characterized by: (1) hands and feet without webbing; (2) connected lateral metatarsalia; (3) presence of an inner metatarsal tubercle; (4) absence of an outer metatarsal tubercle; (5) absence of maxillary and vomerine teeth; and presence of a largely distensible, single subgular vocal sac (males) (Glaw and Vences, 2007).

“Slow motion” movements are typical for members of this genus, especially for the small species, although disturbed *Stumpffia* can perform long jumps. As far as is currently known, development in the genus takes place in terrestrial foam nests deposited in the leaf litter, where the non-feeding tadpoles develop into tiny froglets (Glaw and Vences, 1994). At this point in time this mode of reproduction appears to be unique within the family Microhylidae.

Until recently the taxonomy of this genus was unclear and was in need of comprehensive revision (Glaw and Vences, 2007). However, in a molecular phylogenetic analysis, Wollenberg *et al.*, (2008) provided evidence for the polyphyly of the genus as currently recognized, with a northern, western and a southerly distributed clade, respectively. Consequently, western and southern species should be placed in new genera, as the type species of the genus *Stumpffia psologlossa* originates from Nosy Be, northern Madagascar.

New species of *Stumpffia*

***Stumpffia hara* sp. nov.**

***Stumpffia be* sp. nov.**

***Stumpffia staffordi* sp. nov.**

***Stumpffia megsoni* sp. nov.**

Recent surveys of the herpetofauna in selected locations throughout northern Madagascar revealed the existence of four new species of *Stumpffia*. Two of these species are larger than all previously known taxa, but all clearly belong to this genus based on molecular phylogenetic relationships. All four species have fully developed digits, are closely related and occur in karstic limestone environments, with most specimens collected in caves, a habitat formerly unknown for cophylines.

This newly discovered radiation of large-bodied and apparently cave-dwelling *Stumpffia* contains a species from Nosy Hara, Ankarana, Ampombofofo and Montagne des Français, respectively. In the latter species, specimens can reach lengths of up to 28 mm snout–vent length. These new species are genetically differentiated from each other by 3.8 – 8.6% pairwise divergence in the 16S rRNA gene and furthermore by differences in coloration, extension of terminal finger discs, relative eye diameter and relative head width.

Given the generally high degree of micro endemism in *Stumpffia* (and cophylines in general) it seems likely that they are restricted to very small ranges (all four species have a known area of occupancy of <20 km^2 and appear to occur at only 1–2 locations per species). However, due to their specialization to karstic habitat and partly to caves, they are probably less affected by deforestation than other Malagasy frog species (see Andreone *et al.*, 2008b). Nevertheless, all are prone to the effects of human activities or stochastic events. Therefore, according to the International Union for Conservation of Nature criteria, all are currently classified as ‘‘Vulnerable’’D2.

Family Colubridae

Oppel, 1811

The Colubridae comprises some two-thirds of the World’s 3000 or so known species of snakes (Zug *et al.*, 2001). In virtually every region (Australia being a notable exception) this family represents the dominant group of terrestrial snakes, and its members are found in almost every conceivable habitat from sea level to the highest mountain forests, including areas within the Arctic Circle (Stafford, 2006). Characteristic features of modern colubrids include the absence of girdle and limb elements, a functional left lung, and coronoid bone (a small bone in the lower jaw retained by primitive snakes) (Stafford, 2006). Some species have teeth that are unmodified (aglyphous), while others have enlarged grooved maxillary fangs mounted toward the back of the upper jaw (opisthoglyphous), usually connected to a poison-producing salivary gland (Duvernoy's gland) (Stafford, 2006).

Colubrids are the most diverse snake group in Madagascar, whether considered from the standpoint of species diversity or that of ecomorphology (Cadle, 2003). At present, 75 species, from 18 genera, are recognized from Madagascar, but several additional species (at least) still await their formal description (Glaw and Vences, 2007). Most Malagasy genera (and all species) are endemic to Madagascar, with the exception of *Liophidium mayottensis* (which is endemic to Mayotte) and *Leioheterodon madgascariensis* (which has been introduced to Grande Comoro) (Glaw and Vences, 2007).

Knowledge of the systematics and relationships of the Malagasy colubrid radiation is still poorly understood and controversial (Glaw and Vences, 2007). In part, the difficulties arise from a relatively poor understanding of the relationships among colubrids worldwide, including whether the family is monophyletic (Cadle, 1994). However, recent molecular studies have led to considerable progress at different levels (Glaw and Vences, 2007). All Malagasy colubrids (with the exception of the montypic *Mimophis mahfalensis*, which is closely related to other psammophiine snakes of Africa [Cadle, 2003]), belong to a single radiation, the

Pseudoxryrhophiinae, which also includes a few species from the Comoro Islands, Socotra Island and possibly South Africa (Glaw and Vences, 2007).

The genus *Liophidium*

Boulenger, 1896

The genus *Liophidium,* currently contains eight species of snake, including seven Malagasy taxa and one species (*Liophidium mayottensis*) which is endemic to the Island of Mayotte in the Comoros. *Liophidium* has not been subjected to a comprehensive revision since the work of Domergue (1984) who described three new species (*Liophidium apperti*, *Liophidium therezieni* and *Liophidium chabaudi*). However, a recent molecular study (Glaw *et al.*, 2007) suggests that there is close relationship with the genus *Liopholidophis*. The monotypic *Pararhadinaea* Boettger, 1898, may also be related to *Liophidium*. Further analysis is required in order to fully comprehend the systematic and relationships of this genus (Glaw and Vences, 2007).

All members of this genus are small, diurnal and terrestrial in nature (Glaw and Vences, 2007). With regards to external morphology, species of this genus are morphologically rather similar. The Malagasy species are characterized by: (1) 17 dorsal scale rows at midbody; (2) a divided anal scale; (3) divided subcaudals; (4) 0-1 loreal scales; and (5) round pupils (Glaw and Vences, 2007).They also possess hinged, specialized blunt, distally compressed teeth that allow for feeding on lizards that have a dense protective layer of osteoderms underlying the body scales (e.g. gerrhosaurids f the genus *Zonosaurus*) (Cadle, 1999).

New species of Liophidium

***Liophidium maintikibo* sp. nov.**

Field work conducted by another research team in the dry deciduous forest of Kirindy, western Madagascar, revealed a distinctive new species of pseudoxyrhophiine snake. Although this new species is not thought to occur in the Antsiranana province its formal description was greatly aided by the data gathered by the new survey programme in the extreme north of the Island. New data regarding *Liophidium therezieni* (e.g. morphological and distribution data from new specimens) was particularly useful.

Liophidium maintikibo is clearly assigned to this particular genus by molecular data. It is most closely related to *Liophidium therezieni* but differs by a lower number of ventral scales and several details of coloration. Its ventral scales have a large central black patch which is missing from the subcaudals. This predominantly black ventral side is similar to that of another enigmatic Malagasy snake, *Pararhadinaea melanogaster*. The phylogenetic relationships of *Pararhadinaea melanogaster* (the sole representative of a monotypic genus) have so far not been clarified. Similarities to *Liophidium maintikibo* may indicate affinities to *Liophidium*, but *Pararhadinaea melanogaster* differs from this new species by a lower number of ventrals, subcaudals, number of maxillary teeth and by a different dorsal colouration.

Liophidium maintikibo is currently known from a single specimen, *Liophidium therezieni* from seven specimens, and *Pararhadinaea melanogaster* from five specimens. In almost all cases only a single specimen of these species was collected from one locality. Nevertheless, data generated by the new research programme indicates that the extent of occurrence of these snakes is not necessarily small. *Pararhadinaea melanogaster* and *Liophidium therezieni* may in fact occur across northern Madagascar and *Liophidium maintikibo* (if the Ampijoroa locality is confirmed) across a wide range in the West and North West. Whether the extreme rarity of captures reflects real rarity of these snakes in their environments or is merely a consequence of their secretive habits remains to be studied. Therefore, according to the International Union for Conservation of Nature criteria, *Liophidium maintikibo* is currently classified as Data Deficient.

CHAPTER 5: ANTHROPOGENIC ALTERATION

Detrimental Activities

Socioeconomic factors such as rapid population growth, poor education and other particular aspects of Malagasy culture are partly responsible for obliging local residents to employ harmful agricultural methods and other activities that lead to the exploitation of natural resources (Durbin *et al.,* 2003). As a result of their close proximity to urbanized areas (e.g. the administrative capital of the Antsiranana province) and more rural neighbouring communes (e.g. villages such as Andavakoera) the unique herpetofauna of the Antsiranana province is vulnerable to these anthropogenic pressures (Megson *et al.*, 2009).

Fieldwork, conducted during this new research programme, has identified that the major threats to herpetofauna of these areas are: (1) agricultural clearance for banana, coffee, khat, maize, papaya, sugar apple, and rice cultivation; (2) charcoal production;

(3) timber production; (4) small scale quarrying; and (5) zebu grazing (during which sites are either selectively logged or cleared of all trees) (D'Cruze *et al.*, 2007; D'Cruze *et al.*, 2008; Megson *et al.*, 2009). All of these threats have resulted in the degradation or clearance of large areas of forest in both protected and unprotected areas. Continued forest clearance will lead to the eventual fragmentation of the remaining areas of forest (with serious consequences on herpetofauna, e.g. Vallan, 2000).

Factors Affecting the Impact of Habitat Loss

The impact of these types of habitat alteration (and subsequent degradation or loss) on forest communities can be determined by a variety of factors such as (1) the habitat type (Vallan, 2002); (2) the size and shape of the affected site (Scott *et al.*, 2006); (3) the type of anthropogenic activity (Greenberg *et al.*, 1994; Ryan *et al.*, 2002); and (4) the landscape context (e.g. proximity to other critical habitats; Greenberg *et al.*, 1994; Ryan *et al.*, 2002). Furthermore, it is not uniform across species or taxonomic groups (Vallan, 2002; Lehtinen and Ramanamanjato, 2006; Scott *et al.*, 2006) and a given anthropogenic activity may have differential effects in terms of a reduction or increase in abundance or occurrence (Ryan *et al.*, 2002; Andreone *et al.*, 2005). Perceptions of the effects may be determined in part by the design of monitoring programmes (e.g. see Petranka *et al.*, 1993; Ash and Bruce, 1994; Ryan *et al.*, 2002) as well as the specific methods used to perform censuses (Heyer *et al.*, 1994; Hanlin *et al.*, 2000; Ryan *et al.*, 2002), and the time period over which monitoring is conducted (Pechmann, 1991; Gibbons *et al.*, 1997; Ryan *et al.*, 2002).

Previous Studies conducted in Madagascar

For conservation and land management purposes it is essential to identify susceptible species and understand how species and animal communities respond to anthropogenic habitat alteration (Scott *et al.*, 2006). In Madagascar, such studies have been conducted in tropical rain forest (e.g. Stephenson, 1993; Vallan, 2000), littoral forests (e.g. Lehtinen *et al.,* 2003; Watson *et al.,* 2004), spiny forest (Scott et. al., 2006) and until recently have mainly focused on protected areas (e.g. Stephenson, 1993; Goodman and Rakotondravony, 2000; Vallan, 2000). In comparison, relatively little research has been undertaken in the mostly unprotected transitional forest found in the extreme north of Madagascar, despite the fact that this habitat type is recognized as a high conservation priority (Glaw *et al.,* 2001b; Lavranos *et al.,* 2001). Therefore in order to address this imbalance one such site, located within the unprotected Montagne des Français, was selected as the focus of a new study which aimed to further investigate the impacts of anthropogenic activity on the Malagasy fauna within (D'Cruze and Kumar, 2011).

With regards to amphibians and reptiles, there are relatively few studies of disturbance effects on these particular taxonomic groups (Gardner, 2009) ([but for amphibians see Andreone, 1994; Vallan, 2000; 2002; Vallan *et al.,* 2004; Lehtinen *et al.*, 2003; Glos *et al.,* 2008a,b,c] [and for reptiles see Bloxam *et al.,* 1996; Brady and Griffiths, 1999; Jenkins *et al.,* 1999; Ramanamanjato, 2000; Jenkins *et al.*, 2003; Metcalf *et al.,* 2005; Scott *et al.*, 2006; Rakotondravony, 2007; Young *et al.,* 2008]). Furthermore, with regards to reptiles, the majority of research has focused on chameleons, with the result that comparatively little is known about the disturbance sensitivity of other herpetofaunal taxonomic groups (Gardner, 2009). Therefore, this new research programme deliberately chose to investigate the effects of anthropogenic activities on a particular species (*Phelsuma grandis*) and lizard communities within Montagne des Français (D'Cruze *et al.*, 2009b; D'Cruze and Kumar, 2011).

Lizards were also selected as the focus of this research because: (1) currently limited detailed ecological information is currently available for this taxonomic group in Madagascar (Glaw and Vences, 2007); (2) they are characterised by a high level of endemism (Glaw and Vences, 2007); (3) they are threatened with extinction (Raxworthy *et al.*, 2003; Glaw and Vences, 2007); (4) they commonly occur in all habitats throughout a variety of strata and microhabitats; (5) they possess well defined morphological characters so comparatively identification verifiability is not a major issue (Vences *et al.*, 2008); and (6) they are particularly sensitive to habitat modification and have been commonly used as bio-indicators (e.g. Raxworthy and Nussbaum, 1994; Watson *et al.*, 2004; Scott *et al.*, 2006). In particular, the gecko *Phelsuma grandis* was selected as a particular focus of this research because: (1) it is a regionally endemic species though to be restricted to the extreme north of the island; and (2) it is a large colourful diurnal species making it relatively easy to survey.

Impact on a Species

Initially, this aspect of the research programme aimed to try and gauge the impact of anthropogenic habitat alteration on an individual species. Therefore, during a nine week period, the abundance of the gecko *Phelsuma grandis* was investigated using visual encounter surveys conducted along 75 transects within each of three habitat types within Montagne des Français, north Madagascar (D'Cruze *et al.*, 2009b). In total 91 individuals were observed during the study. Capture rates in village orchards were higher than in clear cut and forest areas. Structural habitat parameters on transects differed significantly between habitats. The orchards and the clear cut areas showed lower structural diversity than forests. Multiple regression analyses showed that the habitat parameters significantly influence the abundance of *Phelsuma grandis*. The best regression model explained 57% of the variation in the abundance of *Phelsuma grandis*. It was concluded that high structural diversity is not important for this species. Results from this study suggest that abundance for this species is positively influenced by higher numbers of trees (perch sites and associated cover) and increases in food resources within orchard habitats.

Impact on Lizard Communities

In addition, standardized field surveys (a variation of Visual Encounter Survey [VES]) were conducted to assess lizard species richness, abundance and diversity among forest, clear cut and orchard habitat types in Montagne des Français (D'Cruze and Kumar, 2011). Unsurprisingly, this aspect of the research demonstrated that forest sites proved to be very different from clear cut and orchard sites with regards to habitat structure. Species richness, abundance and diversity were significantly lower in clear cut sites, with only 11% of the observed forest diversity recorded. This shift in species occurrence suggests that lizards are particularly sensitive to this type of habitat alteration. Orchard cultivation did not affect species richness to the same extent, as 56% of the observed forest diversity was recorded in this habitat type.

Furthermore abundance was significantly higher in orchard habitat. These observations indicate that although anthropogenic activity can have an adverse effect on the lizard fauna of a given site, it will seldom lead to a total loss of diversity as species typical of pristine forest (specialists) are replaced by species adapted to secondary habitats (often generalists). These results support the contention that anthropogenic habitat alteration can have a strong negative influence on lizard communities.

Conservation Implications

This species focused study demonstrated that, the orchard sites supporting *Phelsuma grandis* have a more moderate level of structural diversity than the clear cut or the forested sites. Therefore, we can conclude that unlike some other forest restricted species, *Phelsuma grandis* populations may be less vulnerable to extinction because of continued habitat destruction. However, this species was not abundant in all of the different types of anthropogenically altered habitats present in this region (e.g., clear cut areas). Furthermore, it is regionally endemic and members of this particular genus have additional pressures from collection for the international pet trade (which may represent a larger threat than is currently acknowledged). Recent investigations have highlighted that in certain locations the trade in Malagasy reptiles is rapidly expanding (both in terms of volume and range of taxa) with more “mobile” and “underground” operating mechanisms in utilisation (Todd, 2011). Consequently, a detailed taxonomic, ecological, and conservation focused review of this species and the entire *Phelsuma* genus in Madagascar should be a priority.

As a result of the community focused study, 4 of the 11 encountered lizards (36%) (*Geckolepis maculata*, *Phelsuma abbotti chekei*, *Uroplatus sikorae* and *Zonosaurus tsingy*) can be considered as forest specialists that are highly dependent on relatively undisturbed habitat. Therefore, in light of the ongoing anthropogenic habitat alteration that is occurring throughout Madagascar, they are particularly at risk from local (and possibly total) extirpation. Furthermore, it is also logical to assume that an additional 3 species (27%) (*Blaesodactylus boivini*, *Lygodactylus* c.f. *heterurus*, *Paroedura stumpffi*) are similarly at risk. Although it appears that (like *Phelsuma grandis*) they are able to tolerate anthropogenic disturbance to at least some degree they are all regionally endemic species limited to a select number of forest sites in the extreme north of Madagascar (D'Cruze *et al.*, 2007).

CHAPTER 6: SUMMARY

Contribution to the existing literature

Amphibians and reptiles are important components of many tropical ecosystems, yet as taxonomic groups they are among the least well known of all vertebrate animals (Stafford, 2006). In particular, given the current threats facing its unique biota, the conservation of Madgascars herpetofauna should be a global research priority (Glaw and Vences, 2007). The programme of research on which this synopsis is based represents at least some advancement of knowledge on the amphibians and reptiles of this threatened hotspot of biodiversity. Overall, it elucidates a number of issues pertaining to broader questions of herpetological conservation biology in Madagascar that have been traditionally confounded by a lack of evidence (e.g. phylogeny, biogeography, community composition, and ecology).

Moreover, it represents a significant contribution to the existing literature for a number of specific reasons. Firstly, one study represents the first literature review to specifically characterize the herpetological survey work conducted over a crucial 14 year research period. Secondly, several of these studies represent the first detailed herpetological data for key sites of conservation importance in a recognized area of biological importance. It seems that this work has already helped stimulate the publication of additional similar studies by other independent research groups (e.g. Bora *et al.*, 2010; Durkin *et al.*, 2011; Labanowski and Lowin, 2011). Thirdly, as a direct result of this programme of research six species previously unknown to science have been discovered and described: five microhylid frogs (*Rhombophryne matavy*, *Stumpffia hara*, *Stumpffia be*, *Stumpffia staffordi*, *Stumpffia megsoni*) and one colubrid snake (*Liophidium maintikibo*) (Franzen *et al.*, 2009; D’Cruze *et al.*, 2010; Köhler *et al.*, 2010). Lastly, the anthropogenic habitat alteration focused studies (D’Cruze *et al.*, 2009b; D’Cruze and Kumar, 2011) represent the first attempts to investigate the impact of such activity on individual lizard species and communities in the mostly unprotected transitional forest found in the extreme north of Madagascar. They also finely differentiate between types and levels of disturbance, including purely anthropogenic landscapes. Vitally, all of this information is now available to herpetological researchers and other key actors who can use this information to guide future conservation focused initiatives.

Limitations of this research programme

As informative as data generated by this new the research programme might be, there are a number of limitations that should be taken into account. Firstly, it is acknowledged that, due to labour, time and expense related constraints, field work was not conducted in all of the key sites of herpetological diversity situated in the Antsiranana province. Many of these sites have been subject to varying degrees of research activity and the resulting information has been published in peer reviewed format (e.g. Ankarana Special Reserve [Hawkins *et al.*, 1990], Lokobe Strict Nature Reserve [Andreone *et al.*, 2003] and Daraina [Rakotondravony, 2006]). However, some sites, to this day, still remain unexplored with no data currently available (e.g. Analamera Special Reserve).

Secondly, it is important to note that the fieldwork associated with this research programme resulted in the discovery of an additional nine species (not specifically mentioned in this synopsis) that also appear to represent undescribed species (*Amphiglossus* sp. nov., *Boophis* sp. nov. aff. *Brachychir*, *Boophis* sp. nov. aff. *madagascariensis* “north”, *Brookesia* sp. nov., *Cophyla* sp. nov., *Madagascarophis* sp. nov., *Paracontias* sp. nov., *Uroplatus* sp. nov. aff. *ebenaui*, *Uroplatus* sp. nov. aff. *henkeli* (D’Cruze *et al.*, 2007; D’Cruze *et al.*, 2008, Megson *et al.*, 2009]). Currently, they represent part of a long list of species (consisting of approx. 150 amphibians alone) that have been identified but await formal naming (Glaw and Vences, 2007).

Thirdly, with regards to the anthropogenic habitat alteration study focused on lizard communities (D’Cruze and Kumar, 2011), it must be acknowledged that some caution is required when interpreting the results. Undoubtedly some species were overlooked during survey efforts. Their absence may be a result capture bias related to: (1) spatial sampling (MacKenzie *et al.*, 2002, 2005); (2) census methods utilized; (3) structural habitat type; and (4) other abiotic influences such as time of day, month or weather (e.g. Blair, 2009). Furthermore, it is acknowledged that this research programme, like the majority of existing research (Gardner, 2009), represents only a "snapshot" of lizard species and community responses to habitat change. In comparison, very little is known about the long term effects on Malagasy herpetofauna resulting from habitat alteration and associated loss.

Future recommendations

Since February 2009, political turmoil and the subsequent regime change have resulted in highly unstable times in Madagascar. Numerous national and international sources have confirmed that illegal resource extractors have taken advantage of this situation and have been involved in an unprecedented level of natural resource pillaging (e.g. illegal forest and endemic fauna harvesting) (Waeber, 2009). It is clear that these activities are responsible for a new conservation crisis for this recognized hotspot of herpetological biodiversity.

Consequently, now more than ever, it is clear that immediate and increased conservation management action is required to protect the herpetological diversity found within the Malagasy province of Antsiranana. While it is true that a great deal of research remains yet to be done, as a result of our research programme, several key recommendations can be provided to help safeguard the diversity of this key area of herpetological importance.

Firstly, in light of the rapid and increasing rates of habitat loss (e.g. Myers *et al.*, 2000; Irwin *et al.*, 2010), it is recommended that more herpetological surveys should be conducted throughout Madagascar (both in protected and unprotected areas) and that researchers should look to work in habitat types that have been traditionally overlooked (D'Cruze *et al.*, 2009a). With specific regards to Antsiranana, researchers should begin by conducting detailed baseline herpetological survey work, resulting in widely accessible peer reviewed publications, for two protected sites in particular: (1) Ankarana Special Reserve for which only a preliminary species list exists (Hawkins *et al.*, 1990); and (2) Analamera Special Reserve for which no formal published data is currently available.

To combat time, personnel, and financial constraints these researchers should strive to improve the design and implementation of all census studies so that they are as effective as possible. This could be achieved in part through increased collaboration with Malagasy researchers and self-funded volunteers, as both groups provide the means by which comprehensive data sets can be collected and both can effectively contribute to long-term surveys (D'Cruze *et al.*, 2009a). Researchers may also consider involving designated members of local communities in participatory ecological monitoring programmes (Gardner, 2009). To complement these efforts, researchers should strive to maximise accessibility to the data generated by their research. This can be achieved in part by utilizing approaches that speed up data availability via appropriate cyber infrastructure (Vences *et al.*, 2008a; D'Cruze *et al.*, 2009a). This will support the increasingly collaborative nature of research on Malagasy herpetofauna.

Furthermore, it is vital to ensure that the information generated by this type of herpetological survey work is analyzed and assessed under the auspices of a broader conservation context. This process has already been conducted for Malagasy amphibians (Andreone *et al.*, 2005) and the majority of described species feature on the Global Amphibian Assessment (GAA) which provides relevant data including IUCN Red List threat category, range map and other ecology information. It is recommended that that the relevant experts also look to build upon an initial workshop (held in January 2011) in order to review the current extinction risks for Malagasy reptiles (Glaw and Vences, 2007).

In order to help underpin these conservation initiatives, taxonomic researchers should continue to focus their efforts on completing an accurate account of all extant species. Currently in Madagascar herpetological taxa are being discovered at a rate greater than at which they can be described (Glaw and Vences, 2007). This is exemplified by this research programme which resulted in the discovery of nine species, seemingly new to science, which still await their formal description. Although as yet no catastrophic declines or extinctions have been detected given the current rates of habitat loss and degradation this seems inevitable (Irwin *et al.*, 2010). Therefore sustained, and if possible increased, taxonomic research effort is required in order to document species before they disappear.

In addition, given the knowledge gaps, researchers should look to conduct applied studies that that assess amphibian and reptile species' ecology, behaviour and health across anthropogenic disturbance gradients, including purely anthropogenic habitats (Irwin *et al.*, 2010; D'Cruze and Kumar, 2011). Furthermore, in order to understand the long term viability of biodiversity, it is also recommended that researchers should also look to initiate more long-term monitoring programmes. This type of detailed long-term analysis is urgently required as it may aid the identification of generalizations desperately needed to guide the course of existing and future conservation-focused management strategies (Irwin *et al.*, 2010).

All of the information generated by the recommendations and associated initiatives listed above should be utilized in order to help produce a detailed conservation management plan for the extreme north of Madagascar (Megson *et al.*, 2009). Based on the data generated by this new research programme, and other information currently available, it is strongly recommended that Montagne des Français should be granted full-protected status so that it is able to function as a biological refuge for the threatened species that seem to be endemic to the extreme north of the island (D'Cruze *et al.*, 2007; Megson *et al.*, 2009). In addition, habitat restoration activity should also be encouraged to improve connectivity with Orangea and the Bobaomby Region so as to address habitat fragmentation (Megson *et al.*, 2009). Lastly, increased conservation management action is required to protect the biological diversity found within the existing protected areas found in the north of the country (e.g. Montagne d'Ambre National Park and the Forêt d'Ambre Special Reserve) (D'Cruze *et al.*, 2008). Without it a number of more widespread concerns acting in combination (e.g. a lack of resources, institutional deficiencies, a lack of political will and corruption) will threaten to undermine both existing and future efforts.

In order to implement this plan in an effective and sustainable manner the following additional conservation-focused initiatives apply: (1) further assessment and monitoring of natural resource use activities; (2) development and implementation of a large-scale, regionally connected, more sustainable community-focused management system; (3) development efforts to promote sustainable agriculture practices and to improve human conditions; (4) implementation of village-based environmental awareness programmes targeting all socioeconomic groups; (5) Development of small-scale eco-tourism at key sites as a workable alternative to non-sustainable resource use; and (6) establishment of enforcement training programmes to produce forest wardens for existing protected areas (D'Cruze *et al.*, 2007; D'Cruze *et al.*, 2008; Megson *et al.*, 2009).

Conclusion

In order to conserve the unique herpetofauna of Madagascar it is important that researchers continue to collate the necessary data required to inform existing and guide future conservation management strategies. It is hoped that this synopsis, and the programme of research upon which it is based, represents at least some advancement of knowledge on the amphibians and reptiles of this threatened hotspot of biodiversity. Furthermore, it is hoped that it also serves to demonstrate the importance of baseline herpetological survey work, and the additional information that they can generate, for achieving these conservation goals.

CHAPTER 7: LITERATURE CITED

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CHAPTER 8: SUBMISSIONS

1. D’Cruze, N., Henson, D., Olsson, A. & Emmett, D. (2009). The importance of herpetological survey work in conserving Malagasy biodiversity: Are we doing enough? *Herpetological Review*. 40, 19-25.
2. D'Cruze, N.C., Sabel, J.A., Green, K., Dawson, J., Gardner, C., Robinson, J., Starkie, G., Vences, M. & Glaw, F. (2007). The first comprehensive survey of

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