# LEMUR-ENVIRONMENT RELATIONSHIPS IN ALTERED AND UNALTERED TROPICAL DRY FORESTS IN SOUTHERN MADAGASCAR

By

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## ABSTRACT

# LEMUR-ENVIRONMENT RELATIONSHIPS IN ALTERED AND UNALTERED TROPICAL DRY FORESTS IN SOUTHERN MADAGASCAR

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In this research, I address lemur conservation by extending our ecological knowledge of *Lemur catta* and *Propithecus verreauxi* population density and spatial distribution outside of protected lands. The goal was to better understand how the two species utilize complex forest landscapes characterized by multiple forest classes with protected and unprotected areas around Beza Mahafaly Special Reserve. The objectives of this study were to create a forest cover map of the study area that characterizes the diversity of forest classes on the landscape; assess *L. catta* and *P. verreauxi* population densities across a 3 km dry forest gradient; and to characterize forest structural and lemur population parameters in adjacent grazed and ungrazed forest sites.

Multi-seasonal satellite data were acquired, from which vegetation indices and textural filters were derived, and then the "randomForest" package in the R statistical program was used to classify the imagery. Using built-in cross-validation, overall classification accuracy was 85% with class accuracies ranging from 63 – 91%. Accuracy estimates were highest for dry deciduous and gallery forest classes and lowest for spiny forest. This new map may help expand our definition of lemur habitat in this study area.

The study of southern dry forest lemurs has been largely restricted to small reserves, yet, the majority of the region's lemur populations reside outside of protected areas. Despite their sympatry (i.e., occupation of the same habitat), no previous studies have compared the concurrent densities in any single forest class—much less across forest classes. This study assessed *L. catta* and *P. verreauxi* population densities across a 3 km dry forest gradient in southern Madagascar.

The highest densities recorded for each species were in the protected area;. *L. catta* density was highest in protected gallery forest and *P. verreauxi* density was highest in protected dry deciduous forest. Outside of protected areas, this partioning of habitat was not observed. Both species' density was relatively high in unprotected gallery forest. Results of this study indicate that patterns of lemur density in protected areas are not representative of patterns in disturbed forests; this also suggests that we cannot fully understand the ecological constraints facing primate species by studying them only in protected areas. This research highlights the value of pairing the study of regional patterns of species distribution with local ecological interpretations; information from only one level may give an incomplete view of the community.

The primate-livestock issue in the dry forests of southern Madagascar is a fairly unique case of wildlife-livestock interaction. Grazing impacts on forest structural parameters appear to be more pronounced in the dry forest than in gallery. There was no significant difference in either lemur species' densities between the grazed and the ungrazed sites; however, comparisons by forest class captured differences that otherwise would have gone undetected. Results suggest that grazing activities that do not significantly alter forest structure may support lemur densities similar to those in ungrazed areas. However, *P. verreauxi*, in particular, seems sensitive to changes in forest structure in their preferred habitat.

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#### CHAPTER 1 – INTRODUCTION

As the only two diurnal lemurs in Madagascar's southern dry forests, ring-tailed lemur (Lemur catta) and Verreaux's sifaka (Propithecus verreauxi) are the largest remaining extant lemurs in the region. (A third introduced, and since hybridized, diurnal species, *Eulemur rufus*, is also present at Berenty Special Reserve in the southeast) (Mittermeier et al. 2006). The ring-tailed lemur's iconic tail and the "dancing" sifaka lemurs are familiar to adults and children alike. Thanks in large part to the ease of observing them at Berenty Private Reserve, these two species have been popularized in photos and film (Animal Planet's Lemur Kingdom, Universal Pictures' Fierce Creatures (written by self-described lemur devotee John Cleese), Nature documentaries A Lemur's Tale and In the Wild - Lemurs with John Cleese, DreamWorks' animated film, *Madagascar*, PBS' *Zoboomafoo* (a Coquerel's sifaka similar to Verreaux's)). In a region otherwise comparatively depauperate of the island's endemic primate fauna, these two lemurs are the region's (and indeed, the nation's) flagship species (Durbin 1999, Walpole and Leader-Williams 2002, Jolly 2003b)—charismatic symbols of the ecosystem that serve to stimulate conservation awareness in the region (Hawksworth et al. 1995, Simberloff 1998). The majority of their populations live outside of protected areas, yet the bulk of ecological studies conducted on the two have focused on populations in small protected areas where human impacts are comparably minimal (e.g. (Richard et al. 1993, Jolly and Pride 1999, Jolly et al. 2002, Gould et al. 2003)).

In this research, I address lemur conservation by extending our ecological knowledge of *L. catta* and *P. verreauxi* population density and spatial distribution outside of protected lands. The goal is to better understand how the two species utilize complex

forest landscapes characterized by multiple forest classes with protected and unprotected areas. It is especially important to have a clear understanding of lemur habitat outside of protected areas now that Madagascar National Parks is in the process of expanding the country's protected areas network (Madagascar National Parks). Furthermore, the research may provide insight into the nature of the species' "physiological and behavioral flexibility" in highly seasonal and highly variable environments (Sauther 1998).

## **Objectives**

- Mapping potential lemur habitat
- Modeling the distribution of the *L. catta* and *P. verreauxi* within this potential habitat (i.e., realized habitat)
- A preliminary assessment of human influence on habitat

1) Mapping a tropical dry forest landscape of southern Madagascar (Chapter 2) To date, much of the remote sensing research on tropical forests worldwide has been concentrated on efforts to quantify the extent and loss of large-scale rain forests (Nelson and Horning 1993); there has been comparably less remote sensing research conducted on tropical dry forests (Sanchez-Azofeifa et al. 2003). The delineation and classification of Madagascar's southern dry forests remain little studied outside of country-wide forest mapping efforts (but see (Elmqvist et al. 2007)). Despite their value for some environmental applications, national maps are less useful for applications at the landscape (100-1500 ha), watershed (1000s ha), or even the regional (10,000s ha) levels where thematic accuracy and differentiation between forest classes is of greater importance. I describe a land classification method that discriminates well between the three dominant dry vegetation classes in the study area.

2) Mapping the spatial distribution of *L. catta* and *P. verreauxi* lemurs in a 1500 ha landscape in southern Madagascar (Chapter 3)

There is anecdotal evidence that catta and sifaka partition macrohabitats (Morris 1987) (e.g. exhibit preferences for different forest classes along a dry-forest gradient (Sussman and Rakotozafy 1994)), yet, no previous studies have compared the concurrent densities of these two sympatric species in any single forest class—much less across forest classes. This research combines a regional model of species abundance and distribution with finescale ecological observations, such as forest structural properties, in order to elucidate patterns that may otherwise be obscured at just a single level (Maurer 1999).

3) Comparing forest structural parameters and lemur density between grazed and ungrazed sites (Chapter 4)

Utilizing areas with and without exclusion fencing, comparisons were made between grazed and ungrazed forest sites to explore differences in forest structure and lemur density. I hypothesized that grazed forest regions would exhibit significantly higher levels of disturbance—as evidenced by parameters such as higher percent canopy openness, lower tree basal area, and uncharacteristic tree species composition—than ungrazed regions. Since lemur food resources are reduced for both lemurs (Richard et al. 2000, Gould 2006, Sauther and Cuozzo 2009) and livestock during the dry season, I expected lemur density to be higher in the ungrazed sites where lemurs do not directly compete with livestock for under-canopy resources, and indirect livestock impacts are not present.

#### **Study Area**

The area around Beza Mahafaly Special Reserve was selected as the study area for the following reasons: 1) there is abundant information available about the ecology of both lemur species within the reserve; 2) the study area includes the three representative forest classes of the dryland forests of this region; 3) reserve staff are members of neighboring communities (and in some cases, herders, themselves), and, in addition to having expertise in the local flora and fauna, they are also knowledgeable about present and past land use practices in the area; 4) humans exploit the forest resources in the area in different ways, yet, at least one area is presently protected from livestock grazing and forest products extraction.

The 1,539 ha study area includes both the 600 ha Beza Mahafaly Special Reserve, as well as surrounding unprotected forested lands (Figure 1.1). The entire reserve is embedded in a human-dominated landscape with human activities taking place both outside and within. The reserve (44°37' East, 23°39' South) is located in southwestern Madagascar, 35 km northeast of Betioky Sud, and it consists of two discontiguous parcels (Figure 1.1). Forest structure and composition vary by soil moisture and soil type, with taller trees occupying the wetter soils closer to the Sakamena River, and denser stands of shorter trees found on drier soils (Lowry et al. 1997, Sussman and Ratsirarson 2006). Conditions along this moisture gradient have resulted in three distinct forest classes. Gallery forest is found predominantly along the Sakamena River and is dominated by *Tamarindus indica* (Fabaceae). Gallery forest grades into dry deciduous forest approximately 500 m from the river, and common species in the dry deciduous forest include *Acacia bellula* (Fabaceae), *Salvadora angustifolia* (Salvadoraceae), *Euphorbia tirucalli* (Euphorbiaceae) and trees in the genus *Grewia* (Malvaceae). Spiny forest is the

driest of the three classes and common species here include *Alluaudia procera*—of the endemic family, Didiereaceae—*Commiphora* sp. (Burseraceae), *Gyrocarpus americanus* (Hernandiaceae), *Cedrelopsis grevei* (Ptaeroxylaceae), and *Euphorbia tirucallii* (Eurphorbiaceae). The area experiences a pronounced dry season from approximately May to November each year, with tree species undergoing senescence during the latter half of this period.

At 80 ha, Parcel I is the smaller of the two, and it is the site where most studies have been conducted (e.g., see Sussman and Ratsirarson (2006) for a summary of previous studies) (Figure 1.1). A barbed-wire fence was erected in 1979 (and underwent repairs in 2007) to demarcate the Parcel boundaries and to exclude livestock. Trails were cut for research activities thereafter, creating a network of approximately 100 m square plots (Sussman and Ratsirarson 2006). Prior to the construction of the fence, this parcel was utilized for livestock grazing. The regular presence of reserve staff and researchers in this small parcel, combined with the barbed-wire fence, have been largely effective at preventing livestock grazing. Parcel I comprises both gallery and dry deciduous forest. Unprotected forests immediately adjacent to Parcel I have a similar forest composition, are still utilized by local people, and are degraded to varying degrees. The Reserve campsite and reception area are situated approximately 800 m east of the southwestern corner of Parcel I.

Parcel II, at 520 ha, is situated from 0.5 to 4 km west of the Sakamena River and consists largely of dry deciduous and spiny forests, although it is dominated by spiny vegetation (Figure 1.1). Human activities in Parcel II (sanctioned and otherwise) include agricultural conversion, hunting (mainly birds and tortoises), gathering, livestock grazing,

fuelwood collection, and selective logging (primarily for construction wood). In 2007, reserve staff sporadically patrolled the southern-most end of Parcel II for illegal felling of *Alluaudia procera*; otherwise, on the ground, there was little difference in land use activities outside the reserve and inside Parcel II. In order to discern differences in lemur density between areas closed to human activities and those open to human activities, Parcel I was identified as the only *de facto* "protected area" in this paper; although, legally, both Parcels make up the formal protected area.

The majority of agricultural fields in the study area—many converted from forest by local residents within the past 25 years (2007 conversation with Efiteria; unreferenced)—are concentrated along the Sakamena River at the eastern edge of the study area. Livestock grazing by goats, sheep, and cattle occurs in all forests in the study area except within Parcel I (although, on occasion untended goats have breached the fence and gained entry for short periods of time). Collection of wood for fuel, building, and/or livestock fodder also occurs within all forests except Parcel I.

#### **Ecological Community**

Compared to most Malagasy protected areas, lemur species diversity in the study area is low with only two diurnal species, *L. catta* and *P. verreauxi* (hereafter refereed to as catta and sifaka, respectively), and three nocturnal species: gray mouse lemur, *Microcebus murinus*; reddish-gray mouse lemur, *Microcebus griseorufus;* and whitefooted sportive lemur, *Lepilemur leucopus* (Mittermeier et al. 2006). Catta and sifaka both consume a mix of leaves, flowers, and fruits (Yamashita 2002, Simmen et al. 2003). The diet of the mouse lemurs is varied but consists largely of invertebrates. They also

consume fruits, flowers, and gum but not foliage (Mittermeier et al. 2006). Conversely, the lepilemur diet consists primarily of leaves. (Nash 1998).

The two diurnal species were chosen for study for five reasons: 1) they are flagship species for the region; 2) they share the same forests, but they have different dietary preferences; 3) population density in protected areas appears to vary by forest class; 4) as occasional terrestrial folivorous feeders, they may be competing with livestock for food resources; and 5) their density can be readily estimated without capturing individuals because they can be effectively spotted and heard from stationary sampling locations.

Catta is a fairly large lemur (2.3-3.5 kg) living in female-dominated groups of 6-24 animals with an average group size in protected subtropical dry forests of 11.5-16 non-infants (Sussman 1991, Jolly et al. 2002, Gould et al. 2003). It is the most terrestrial of all lemurs (Goodman et al. 2006), spending a considerable proportion of its time travelling and feeding on the ground, especially during the dry season. Catta is largely herbivorous, consuming a varied diet of fruits, leaves, herbs, and flowers, depending on resource availability (Sauther et al. 1999). *Tamarindus indica* is an important food source for catta, since it is the only species it feeds on throughout the year (Simmen et al. 2006).

At 3-3.5 kg, sifaka is one of the smaller sifakas. It, too, lives in female-dominated groups, although they are typically smaller than those of catta (range: 2-14 individuals (Richard et al. 2002)). Even though it is a vertical clinger and leaper, it also descends to the ground to travel and feed. This sifaka species is highly folivorous and includes a

higher diversity of plant species in its diet than does catta (Yamashita 2002, Simmen et al. 2003).

Natural predators at the site include raptors and snakes, as well as two introduced mammalian predators, domestic dogs (*Canis lupus familiaris*) and wildcats (*Felis silvestris*) (Mittermeier et al. 2006, Brockman et al. 2008). The drylands of the south pose unique risks for lemurs including extreme variability in resources, competition for food resources with livestock, and loss of habitat due to agricultural expansion and fuelwood collection; yet, we know very little about either the population status of the vast majority of the species' populations, or how that status may vary with disturbance outside of protected areas. Consequently, we cannot, therefore, estimate the level of protection afforded by extant protected areas.

Livestock breeding is a central component of Malagasy life in the south. There are two prevailing livestock grazing practices in the region: *midada* in which livestock roam freely in the forests and are periodically gathered by their owners; and *miarakandrovy*, in which livestock are herded by day and enclosed by night, either in the village or in forest corrals (Ratsirarson 2003). Increases in cattle thefts have forced herders to reduce mobility of their cattle and secure them in forest corrals at night, potentially concentrating impacts in forested areas (Ratsirarson et al. 2001). The literature is replete with examples of interactions between livestock and large native grazers, but this appears to be one of the first examples of direct livestock competition with terrestrial-feeding folivorous primates.

Given the amount of land in the southern ecoregion in use for grazing, it is important to better understand how lemurs respond to grazing pressure. Results from this

study are expected to provide some understanding of the effects of livestock use on lemur populations, to assist in appropriate conservation management of the reserve (including the region between the two parcels which was incorporated into the Reserve in 2009), as well as aid in the design of participatory conservation and forest management programs in which local communities play an active role in management and restoration of forest biodiversity. It is expected that results of this research will also enhance the decisionsupport capabilities of the Malagasy government and conservation organizations working in this ecoregion; this will enable effective management of the Malagasy subtropical dry forest and spiny thicket landscapes for both conservation and economic development goals. Much of the biophysical data collection will also advance other habitat-species projects, as one goal is simply to determine an effective method for characterizing the region's dry forest structure using remotely sensed imagery.



Figure 1.1 The study region at Beza Mahafaly Special Reserve

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# CHAPTER 2 - RANDOM FOREST CLASSIFICATION OF TROPICAL DRY FORESTS IN AND AROUND BEZA MAHAFALY SPECIAL RESERVE, MADAGASCAR

#### Abstract

Ecologists who wish to use maps to describe species habitat often find that available map products created for other management purposes fail to characterize the complexity of the landscape. Researchers studying lemurs in Beza Mahafaly Special Reserve in southern Madagascar have been working for decades without adequate land cover maps of the area. Three dry forest classes and a non-forest class were mapped in and around Beza Mahafaly Special Reserve using the decision tree classifier, Random Forest, and multiseasonal imagery. The semi-arid study area consists of discontiguous protected parcels of dry forest embedded in a human-dominated landscape; major human disturbances include wood collection, livestock grazing, and lopping of trees for livestock. The objectives of this study were to first, create a forest cover map of the study area that characterizes the diversity of forest classes on the landscape, and then to compare its performance to other forest cover maps available for the area. Multi-seasonal ASTER and Landsat ETM+ data were acquired, from which vegetation indices and textural filters were derived; these data, in addition to spectral bands, were then used to classify the imagery using a Random Forest classifier. Using built-in cross-validation, overall classification accuracy was 85% with class accuracies ranging from 63 - 91%. Accuracy estimates were highest for dry deciduous and gallery forest classes and lowest for spiny forest. Classification of spiny forest as dry deciduous accounted for the majority of

misclassifications. The forest cover map was more accurate—especially with respect to forest class diversity—and more precise than other available maps of the study area's forests. This new map may help expand our definition of lemur habitat in this study area.

## Introduction

Globally, tropical forests account for the majority of the earth's remaining forest resources (Hansen et al. 2010). Twenty-five years ago, tropical dry forests outnumbered tropical humid forests nearly two-to-one (Murphy and Lugo 1986), but today, land occupied by tropical humid forests surpasses that of tropical dry forests (Hansen et al. 2010). Dry forests are presently the most endangered tropical forest (Janzen 1988, Miles et al. 2006), as they are at high risk of disturbance from a variety of human activities such agricultural conversion, hunting and gathering, livestock grazing, fuelwood collection, and selective logging (Murphy and Lugo 1986, Miles et al. 2006, Hansen et al. 2010). Tropical dry forests also support a higher human population than do tropical humid forests (Gerhardt and Hytteborn 1992).

Despite their high levels of floristic diversity (Gentry 1995), tropical/subtropical dry forests have historically received far less attention from the conservation community than have humid tropical forest types (Sánchez-Azofeifa et al. 2005, Miles et al. 2006). This has been especially true in Madagascar where the country's rain forests have garnered relatively more international attention than have the island's dry forests (Hannah et al. 2002), despite the fact that estimates place dry and spiny forest loss rates equal to, or even higher than that of Malagasy rain forests (Harper et al. 2007, Moat and Smith 2007).

The dry forests of southern Madagascar take many forms (Battistini 1964, Morat 1973, White 1983), and lemur researchers working in Madagascar's southern dry forests have noted this diversity within even very small study areas ( $<1 \text{ km}^2$ ) (Sussman and Rakotozafy 1994, Jolly et al. 2006, Sussman and Ratsirarson 2006). Interbreeding lemur

populations are often interspersed throughout multiple dry forest habitats, most notably in Beza Mahafaly Special Reserve, Lake Tsimanampetsotsa National Park, and Berenty Private Reserve; furthermore, lemur population density in dry forests has been known to vary by habitat (Budnitz and Dainis 1975, Sussman 1991, Jolly et al. 2002), yet there is neither a clear agreement by researchers on the definition of the habitats types, nor available geo-referenced habitat maps with resolution sufficient for lemur habitat mapping. Currenty available digital map products—although admittedly probably not designed for local scale mapping projects such as these—are woefully inadequate for researchers looking to illustrate findings they've observed on the ground in these heterogeneous landscapes. There's a clear need for map products which will allow researchers to better examine the effects of habitat difference on lemur distribution, and today, remote sensing techniques provide a means for achieving this goal.

To date, much of the remote sensing research on tropical/subtropical forests has focused on the quantification and monitoring of large rain forest landscapes (Rosenqvist et al. 2000, Achard et al. 2002, Hansen et al. 2008), especially in Amazonia (Tuomisto et al. 1994, Salovaara et al. 2005) and Africa (Green and Sussman 1990, Laporte et al. 1995, De Grandi et al. 2002). There has been, comparably, less remote sensing research on tropical dry forests (Sanchez-Azofeifa et al. 2003). Research in Madagascar is a prime example of this trend; Madagascar's status as the single highest priority area on Earth for conserving primate diversity (Mittermeier et al. 2006) has resulted in mapping efforts focused primarily on the island's rain forests (Green and Sussman 1990, Agarwal et al. 2005, Ingram and Dawson 2005), which serve as vital habitat for the majority of the country's endemic lemur species. The landmark deforestation study by Green and

Sussman underscored Madagascar's dire situation by depicting Madagascar's forest loss through time. Smith (1997) conducted a deforestation study of western dry deciduous forest analogous to Green and Sussman's, but Smith's study has received much less attention in the scientific community, with only 51 Google Scholar count citations as of 11 November 2010 vs. 324 for Green and Sussman's study (but see caveats of Google Scholar count citations in (Harzing and van der Wai 2008)). The island's southern dry forests have not been the subject of mapping efforts outside of national forest mapping projects (but see (Elmqvist et al. 2007)).

National vegetation maps have filled an important gap in our knowledge of forest distribution in Madagascar and are useful for large-scale conservation efforts. Botanists have proposed numerous classification systems to organize Madagascar's high floristic diversity. Some systems rely largely on floristics and biogeography, while others strive for a more ecological classification of vegetation types. The first vegetation maps of Madagascar established a hierarchical system based first, on climatic conditions and second, on floristics or phytogeography (Gautier and Goodman 2003). The result was a vegetation map characterized by phytogeographic bounded regions nested within areas defined largely by rainfall (e.g., (Perrier de la Bâthie 1921, Humbert 1955)). These maps were later used as a framework to crosswalk the phytogeographic classification to a vegetation classification resulting in the "Vegetation Map" produced by Humbert and Cours Darne (1965) based on Humbert's (1965) vegetation classification system (Gautier and Goodman 2003).

The first national map effort using remote sensing technology was Faramalala's (Faramalala 1988, 1995) update of Humbert's 1965 vegetation map (Humbert and Cours

Darne 1965) based on aerial photos from the 1950s. Faramalala's map was based on satellite images from the 1970s with a spatial resolution of 80 m and a scale of 1:1,000,000 (Faramalala 1988). As satellite sensor technology advanced, and accessibility to mapping software increased, additional vegetation maps were produced, many of which were digital products.

Unfortunately, some of the "second" generation maps included only broad, and often poorly defined forest categories such as dense humid, dry deciduous, mangrove, secondary complex, and savannah (Mayaux et al. 2000), and western hardwoods, central grasslands, eastern rainforest, and spiny forest (Nelson and Horning 1993). Others progressed beyond the broad forest categorizations described above. Both Inventaire Ecologique Forestier National (IEFN) (1996) and Du Puy and Moat (1998) endeavored to create maps with greater differentiation between forest classes, while Sussman et al. (2006) took an altogether different approach by mapping regional forest canopy density. The IEFN classification was developed for forest management purposes and classes were "distinguished by altitude, density of the canopy, rainfall, leaf type, geomorphic position, and tree species" (Foley 2000). Du Puy and Moat (1998) overlaid their map of "Remaining Primary Vegetation" on a map of simplified geology to highlight the diversity of geologic substrates throughout Madagascar, especially in southern and western Madagascar. While the vegetation type is the same in both maps, classification of vegetation by underlying geology underscores the potential for different vegetation types and species composition throughout the "deciduous, dry, southern forest and scrubland" class. The forest canopy density classification created by Sussman et al. (2006) was

developed to be related to *Lemur catta* population density and was derived from 1985 Landsat spectral data.

The latest national mapping effort, known as the Critical Ecosystem Partnership Fund (CEPF) Vegetation Map of Madagascar (Moat and Smith 2007), may be the most promising for conservation planners. The CEPF Madagascar Vegetation Mapping Project produced an updated vegetation map based on physiognomy (e.g. forest structure). This vegetation classification scheme of 15 mappable units is modeled after White's (1983) continent-wide vegetation map of Africa

Despite their obvious value in some environmental applications, national maps do have limitations, especially for applications at the landscape (100-1500 ha), watershed (1000s ha), or even the ecoregional (10,000s ha) scales where differentiation between forest classes and spatial resolution is of great importance. This is especially true for dry forests which whose structure can vary dramatically within the span of only a few kilometers. National maps may fail to capture the heterogeneity of dryland landscapes. Even in a cases of a quality map scale, dry forests may still be inadequately represented, as spectral resolution of imagery may be too coarse to differentiate between the multiple dry forest classes..

Given the global interest in Malagasy lemurs, it's not surprising that some national mapping efforts were focused primarily on classifying rain forest vegetation; Mayaux et al. (2000) admitted that the dense rain forest class was their "main class of interest" in their SPOT VEGETATION map. Yet, this emphasis may have proven detrimental to the accuracy of other mapped vegetation types, particularly the country's dry forests. Nelson and Horning (1993) noted the difficulty of classifying the entire island

as a single unit; "nonforest cover types in the lush eastern mountains exhibited spectral signatures very similar to forest cover types at the arid southern end of the island". To minimize spectral confusion, they first stratified vegetation into four strata (one of which was spiny forest) and then classified each stratum separately; but it is unclear if this was done on any of the other maps. To further complicate matters, identification of dry vegetation types was not standardized among mapping efforts; for instance, a single patch of spiny forest is identified on three different maps as either "dry deciduous", "dry or spiny forest", or "savannah". A primary goal of national level mapping efforts is to measure changes in forest cover over time, but scientists' use of different vegetation schemes and methodologies in mapping efforts preclude us from making such comparisons (Foley 2000).

As Madagascar National Parks expands the country's protected areas network, it is especially important to have a clear understanding of forest habitats outside of protected areas. Since President Marc Ravalomanana's 2003 announcement to triple the country's protected areas, the Malagasy Government has created 15 new protected areas (Lovgren 2007), including six new parks (Madagascar National Parks, Norris 2006). Two protected areas in southwestern Madagascar have been extended in size, including Tsimanampesotse National Park (Bradt 2007) and Beza Mahafaly Special Reserve (Raharimalala 2008), and a couple of community managed protected areas have been newly designated (Ministère de l'Environnement et des Forêts),

In the Beza Mahafaly Special Reserve, a 600 ha subtropical dry forest reserve, our understanding of forest cover is based primarily on forest species composition surveys in a 100 ha parcel (Sussman and Rakotozafy 1994, Yamashita 2002). Information about

forest cover outside the reserve is very limited, and it may be influenced by what researchers view along the roadside as they drive into the site. The majority of researchers come to BMSR to study lemurs, and despite two decades of research on Verreaux's sifaka (*Propithecus verreauxi*) and ring-tailed lemur, (*Lemur catta*) (hereafter referred to as sifaka and catta respectively) (Sauther et al. 1999, Richard et al. 2002) there is still no fine-scaled forest cover map for the reserve. A finer discrimination is necessary, both for understanding lemur distribution and habitat requirements, and for implementing effective conservation plans in the adjacent forests.

The objective of this study is to map dry forest classes in and around BMSR using spectral and thermal bands, vegetation indices, and texture measures derived from multi-temporal remotely sensed imagery. A decision tree classifier, Random Forest, was selected as it has been recommended for difficult classification problems including those with heterogeneous data (Lunetta et al. 2005, Gislason et al. 2006) and in cases where multi-source data are used (Gislason et al. 2006). Additionally, Random Forest can be a particularly powerful approach to classification in cases where neither a single variable/spectral band, nor a small number of variables (such as a multi-band image) is expected to distinguish between classes (Breiman 2001).

#### Methods

#### Study Area

The Beza Mahafaly study area is described in Chapter 1 (Figure 2.1). *Training Site Sampling for Land Cover Classification* 

Training site data (geographic locations of forest classes identified on the ground) were collected in June-July 2006 and June-August 2007. In total, 461 training site
locations were identified using a Garmin V global positioning system (accuracy <15 m, with nearly all locations collected at  $\leq$  5 m accuracy) fitted with GPS Outfitters Titan III antenna. Training site data were collected in three different dry forest classes—gallery, dry deciduous, and spiny—and in a variety of areas considered to be non-forest (e.g. bare soil, road, agricultural crops, open scattered tree grasslands, and open bushland). Criteria used to characterize each forest class were based on a physiognomic classification following White's (1983) approach to the Vegetation Map of Africa.

Gallery forest was characterized by: a mostly uniform canopy of 15-20 m in height with overlapping crowns of individual trees that often, but not always, form a closed canopy; large-boled trees; and leaf litter layer of  $\geq 2$  cm. Dry deciduous forest was characterized by: a stratified forest of small-boled trees; a rather open upper canopy of typically  $\leq 12$  m in height; well-developed shrub and herb layers; and *Alluaudia procera* emergents rare or absent. Spiny forest was characterized by: a discontinuous, and therefore frequently open, tree canopy layer typically  $\leq 10$  m in height; the presence of the distinctive emergent tree species *Alluaudia procera* and/or the presence of bottle trees (species with distended water-storing stems); the presence succulent plants such as *Euphoribia*; and often a thick bushy vegetation in understory.

#### Random Forest Classifier

Tropical/subtropical dry forest landscapes can be challenging to classify because their numerous vegetation classes have similar spectral properties (Sanchez-Azofeifa et al. 2003). Non-parametric decision trees are well-suited for such complex ecological classification problems (De' ath and Fabricius 2000), and in recent years, their use has increased in land cover mapping, particularly at broad mapping scales (Hansen et al.

1996, Friedl and Brodley 1997, Hansen et al. 2000, Xu et al. 2005). However, their use in highly varied tropical/subtropical landscapes has been limited (but see, (Muchoney et al. 2000, Sesnie et al. 2008). An important advantage to using decision trees over traditional land classification algorithms is that they provide metrics that are useful for discriminating among forest cover classes (Hansen et al. 1996).

Random Forest is one type of tree-based ensemble classification algorithm. Ensemble classification is a fairly new approach to classification in which hundreds of classifiers (in this case, hundreds of classification trees) are built and their decisions combined, usually by plurality vote. The idea is that combining the decisions of many classifiers is often more accurate than using the results from any single classifier (hence the term, "forest" as in Random Forest instead of "tree" as in classification tree).

Random Forest is a "bagging" (bootstrap aggregation) operation (Breiman 2001) which improves overall classification accuracy decreasing the variance of classification errors (Chan and Paelinckx 2008). Bagging is described as follows. For each i decision tree, generate a bootstrap sample from the training data observations of size n (in this case, n = 461). Observations not included in the bootstrap sample are set aside as test data. A decision tree is fit to the bootstrap sample of known forest class observations and then used to predict the assignment of the remaining pixels in the study area. Each pixel, j, will have n<sub>j</sub> "predictions" from the bootstrap models. This process is repeated i times (i=1000, in this case). The class finally assigned to each image pixel in the study area is the one having the majority of predictions from the n<sub>i</sub> prediction. To determine classification error rates, the assigned class of pixels from observations not included in the bootstrap sample is compared to the actual forest class of that pixel. This method

results in randomization of observations in each bootstrap sample. In addition, the number of variables randomly sampled as candidates in each tree split (mtry) can be determined using the tuneRF function. For a detailed description of Random Forest, the reader is referred to the manual

(http://oz.berkeley.edu/~breiman/RandomForests/cc\_home.htm) or Breiman (2001). Very good summaries can also be found in Gislason et al. (2006) and Cutler et al. (2007).

Random forest has numerous advantages over other tree-based classification methods. The approach is robust to over-fitting, pruning of the tree is not necessary, and accuracy is comparable with other modern machine learning methods (e.g. support vector machines, artificial neural networks, Adaboost) (Breiman 2001, Pal 2005). Variables used to predict classification (in this case, satellite image bands) can be continuous and/or categorical, which makes it easy to set-up. There is also built-in cross-validation. Studies indicate that Random Forest's cross-validation can provide a reliable estimate of error, making it unnecessary to create an independent accuracy assessment data set. This is an attractive option for those working with ecological field data, which can be both costly and time-consuming to collect. Lastly, Random Forest can be freely implemented using the R package, randomForest in R software (R Development Core Team 2008). The major disadvantage associated with decision trees is the need for sample sizes of at least 200 when dealing with complex data sets ((i.e. "those with non-linear or high-order interactions") (Joy et al. 2003)).

#### Land Cover Classification

Five cloud-free satellite image scenes (ASTER and Landsat ETM+), two from the wet season (10 February 2005, and 30 March 2005) and three from the dry season (7 July

2006, 9 September 2006, and 28 September 2007) and one ASTER digital elevation model (DEM) were acquired from the U.S. Geological Survey (USGS) (Table 2.1). These dates were chosen to capitalize on seasonal differences in spectral reflectance. The scenes cover Path/Row 160/76 in the Landsat Worldwide Reference System were delivered registered to a Universal Traverse Mercator (UTM) projection using a World Geodetic System 1984 Datum. Landsat images were co-registered to ASTER images, atmospheric correction was applied to all images, and DN values were converted to reflectance. Landsat bands were resampled to 15 m pixel resolution to match that of ASTER bands.

Dry forest classification using spectral classification techniques alone could result in misclassifications due to spectral similarity between leafless forests and pasturelands (Sanchez-Azofeifa et al. 2003), therefore additional information was included in the classification. A suite of vegetation indices considered to be potentially useful indicators of tropical forest attributes was calculated as in Table 2.2 (Feeley et al. 2005). Studies also suggest that multi-date imagery contains information on tree structural properties and phenological stages that has the potential to improve classification accuracies (Tottrup 2004). The thermal infrared band was considered as it may improve mapping of land cover when used alone or in conjunction with vegetation indices (Lambin and Ehrlich 1996). Southworth et al. (2004) found that TM Band thermal band 6 contains information useful for the discrimination among tropical dry forest classes.

The following bands were included in the Random Forest classification: ASTER VNIR spectral bands (visible and near-infrared); vegetation indices as described in Table 2.2; tasseled cap transformations for both Landsat and ASTER images (Dymond et al.

2002, Huang et al. 2002, Yarbrough et al. 2005); difference images between ASTER 02/2005 (wet season) and 09/2006 (dry season) for MSAVI2, SRI, and greenness and wetness bands of the tasseled cap transformation; and the TM infrared thermal band, (Band 6). Also included was a measure of distance of each pixel from the Sakamena River. Textural analyses were included to aid in forest class separability (St-Onge and Cavayas 1997, Tanser and Palmer 2000, Franklin et al. 2001). Textural filters selected for inclusion in the analysis included variance based on the occurrence matrix, as well as second moment, contrast, and entropy all based on the co-occurrence matrix (Haralick et al. 1973). All textural measures were calculated using both 5x5 and 15x15 pixel windows. Spectral and thermal bands, vegetation indices, the DEM, and textural filters were layer-stacked into a single image comprised of 76 bands.

The forest classification was implemented in R version 2.6.2 (R Development Core Team 2008) using the randomForest package (Liaw and Wiener 2002). The resultant model was mapped in ArcGIS 9.2 (Environmental Systems Research Incorporated). Using RF proximities (measures of similarity of data points) (see Cutler et al. 2007), a multi-dimensional scaling graph was plotted to visualize the results of class assignments. Unbiased estimates were ensured by setting the ntree parameter to a point beyond which the test set error converged (Breiman 2001); exploratory graphs indicated that error rates stabilized well before 1000 trees were reached.

## Tree Species Composition of Forest Classes floristics

Given that in many lemur ecology studies forest classes have previously been defined largely by floristics, the forest composition of each of the three forest classes was characterized using data on tree species richness was collected across the study area. A systematic grid (with a random start location) of 404 point samples was overlaid on a map of the study area at separation distances of 115 (in gallery forest) to 300 m (in spiny forest) (Figure 2.2). At each point, all trees within 10 m with a height of 1 m or more were identified to species with the assistance of a Malagasy expert. Tree species composition was calculated for each sample plot.

Point samples were classified as one of four forest classes by the Random Forest classifier. All points classified as non-forest were then excluded from further analysis. The remaining points were separated into three groups based on predicted forest class—gallery, dry deciduous, or spiny. A list of principal gallery tree species was compiled from those tree species present in the majority of each of the forest class sample plots. *Map comparison* 

The Random Forest classification of the study area was compared to four Madagascar forest cover maps available in digital form: Inventaire Ecologique Forestier National (IEFN 1996), Remaining Primary Vegetation (Du Puy and Moat 1998), Vegetation Map of Madagascar (Mayaux et al. 2000) and the Critical Ecosystem Partnership Fund (CEPF) Madagascar Vegetation Map (Moat and Smith 2007). In order to overlay these four map products onto my Random Forest classification, the two vector maps (Inventaire Ecologique Forestier National and Remaining Primary Vegetation) were rasterized to 15 m, and the raster images (SPOT and CEPF Vegetation Maps of Madagascar) were resampled to 15 m. Each map was overlaid on the Random Forest land cover classification in a GIS and the overlap of forest classes calculated.

Du Poy and Moat's (1998) map of Madagascar's remaining primary vegetation is a simplification of an earlier vegetation map digitized by Conservation International,

which was used for rapid biodiversity assessment. The original maps on which the current map is based were derived from Landsat satellite data acquired between 1972 & 1979. The original map was at a scale of 1:1,000,000 and it is expected that the accuracy of this map is around 1 km (Foley 2000).

The National Ecological Forest Inventory (IEFN 1996) map (1:200,000 scale) was based on Landsat TM images from the early 1990s. Visual interpretation was made on color photos of enlarged layer-stacked Landsat imagery and thematic maps were digitized. Results were field verified. Some supervised classification may have also been performed, although this has not been verified (Foley 2000).

Mayaux et al. (2000) derived a forest cover classification from SPOT 4 VEGETATION images dated 1998-1999. The standard VEGETATION ten-day images (image composites created from a stack of daily composites, where each pixel represents the most cloud-free of the ten possible) were too contaminated by clouds and haze in the humid forests region to allow for direct classification; therefore, monthly images were produced in order to reduce the remaining clouds (Mayaux et al. 2000).

More recently, the CEPF vegetation map was completed using Landsat ETM+ images dated 1999-2003 at a resolution of 30 meters. Validation of the vegetation map was undertaken with field data collected through ground surveys. Because a 3x3 pixel filter was applied to output images to smooth the classification, final ground resolution is 90 m. Map scale corresponds to 1:125,000 – 1:250:000 (depending on elevation) with 15 mappable vegetation units (Moat and Smith 2007).

### Results

### Random Forest Classification

The Random Forest classification map includes classification of dry deciduous forest, spiny forest, gallery forest, and non-forest classes (Figure 2.3). Estimated overall accuracy of the forest classification was 85% (Table 2.3). Accuracies for forest classes ranged from 63% for spiny forest to 91% for gallery forest. The largest source of error was associated with spiny forest being classified as dry deciduous forest.

A multi-dimensional scaling plot indicates that the three forest types in the study area can be separated using multi-seasonal remotely sensed data (Figure 2.4). The overlap of dry and spiny forest classes corresponds with results of the confusion matrix (Table 2.3). Initially, the Random Forest classifier was run without textural information, but without the texture, spiny forest was nearly indistinguishable from dry deciduous; inclusion of textural variables greatly improved ability to distinguish between these two classes.

There was also some overlap between dry deciduous forest and non-forest. Given that disturbed dry deciduous forest often has a very open canopy, it may be easily confused with non-forested areas, which themselves have been cleared through disturbance events. The "confusion" between spatially adjacent forest classes also suggests the presence of an ecotone along the environmental gradient as previously noted by researchers working at the site (Sussman and Rakotozafy 1994, Sussman and Ratsirarson 2006).

According to Random Forest's variable importance measure, the most important variable in the classification was distance to river with sample distances ranging 21 – 3455 m from the Sakamena River (Figure 2.5). Other variables of major importance included spectral vegetation indices that capture differences in photosynthetically active

vegetation and soil and leaf moisture (MSAVI2, Greenness Transform, SRI, VCI, difference in MSAVI2). Use of correlated variables, such MSAVI2 and Greenness Transform, is appropriate in a RF since its variable selection procedures allow for use of all predictors of response, regardless of collinearity. Unlike those variable selection procedures which discard a portion of the collinear variables, RF retains all variables and allocates variable importance across all of them (Cutler et al. 2007).

Partial dependence plots illustrate the relationships between individual predictor variables and predicted forest class probability. In Figure 2.6a, the partial dependence plot of distance to river illustrates the importance of this variable in predicting gallery class membership at distances less than 1000 m and predicting dry forest membership beyond 1000 m. The patterns in partial dependence plots for MSAVI2 and Greenness within forest types are remarkably similar (Figures 2.6b and 2.6c); yet, despite these similarities, they are both important in distinguishing between forest classes.

#### Tree Species Composition of Forest Classes

The principal tree species in gallery forest were *Tamarindus indica*, *Quisivianthe papionae*, *Azima tetracantha*, and *Tarenna pruinosum*. Dry deciduous forest included some combination of the following principal species: *Salvadora angustifolio*, *Terminalia seyrigii*, *Tamarindus indica*, *Grewia grevei*, *Acacia bellula*, *Euphorbia tirucallii*, *Cedrelopsis grevei*. Spiny forest was comprised of the following principal species: *Commiphora aprevalii*, *Alluaudia procera*, *Euphorbia tirucallii*. *Gyrocarpus americanus*, *Cedrelopsis grevei*.

#### Map comparisons

The four digital national maps suffer from a lack information about the diversity and spatial arrangement of forest classes and are inadequate for conservation planning in this study area. In addition, there is little consistency of forest class definitions between maps; broad vegetation categorizations and/or the absence of forest classes makes comparison between maps difficult (Table 2.4). Du Poy and Moat's (1998) map (Figure 2.7a) of Madagascar's remaining primary vegetation defines all dry vegetation as a single class, and the final product suggests that Parcel I of BMSR is completely unforested.

Unlike Du Poy and Moat's map, the National Ecological Forest Inventory (IEFN 1996) map does include a suite of dry vegetation classes, but the final product fails to capture the diversity of vegetation classes present in a study area of this size (Figure 2.7b). In the SPOT 4 VEGETATION classification (Mayaux et al. 2000), all dry forest vegetation types were represented by a "dense dry forest" class (Figure 2.7c). In this case, Parcel I is characterized as being fully covered by dense dry forest, but Parcel II is shown lacking any forest cover at all. Given that spiny forest appears to be included in this map's "savannah" class, the map likely underestimates the amount of remaining dry forest vegetation. Furthermore, this map would be unsuitable if one were interested in identifying only gallery forest.

There are also several dry vegetation classes in the CEPF Madagascar Vegetation Map, but these classes do not fully represent the unique vegetation in the south. For instance, the rapidly disappearing gallery forest (Blumenfeld-Jones et al. 2006) is a keystone species for *Lemur catta* (Sauther 1998, Blumenfeld-Jones et al. 2006, Simmen et al. 2006), yet not only is this class not represented in the map, it is unclear into which class it has been classified. Within this study region, at least, gallery forest is classified by

the CEPF map as anthropic, cultivated areas. There was some overlap in the CEFP southwestern spiny dry forest-thicket class and the Random Forest dry deciduous forest class along the Sakamena River, but much of the dry deciduous forest in the area was classified by the CEFP map as cultivated area. There was also significant overlap between CEPF southwestern spiny dry forest-thicket and the Random Forest spiny class. However, the user is not able to differentiate between dry deciduous and spiny forest in the CEPF map. Wooded grassland-bushland was a good match for areas identified by the Random Forest classifier as not forested.

If the goal is to map lemur habitat in southern Madagascar, even the high-quality CEPF mapping effort would be of limited value, as dry deciduous forest and gallery forest classes are indistinguishable from others (Moat and Smith 2007). This is particularly problematic as user's would not be able to hone in on gallery forest, believed to be the preferred *Lemur catta* habitat, or dry deciduous forest, believed to be preferred *Propithecus verreauxi* habitat (Sussman and Rakotozafy 1994). Given that gallery forest in Madagascar is rapidly disappearing (Blumenfeld-Jones et al. 2006), the absence of this vegetation forest class vastly reduces the usefulness of this map for identifying potential catta habitat.

Very little CEPF degraded southwestern spiny dry forest-thicket appeared in the study area, but it is found in large areas of the Madagascar's southern region along the southwest coast. According to Moat and Smith (2007), the locality, physical geography, climate, geology, and soils of both southwestern spiny dry forest-thicket and its degraded counterpart are identical. In theory, the only difference is the level of disturbance; yet, the geographic separation between the two forest classes suggests an ecological distinction.

Overlaying a geological map layer (Du Puy and Moat 1998) over the two southwestern spiny dry forest-thicket classes highlights geological differences between the two; the degraded class falls largely on limestone-derived soils, while the other tends to occur on sandstone-derived or lateritic soils (Besairie 1951, Du Puy and Moat 1998).

#### Discussion

Overall, the Random Forest classification method performed well in discriminating between dominant dry vegetation classes in the study area. Multi-season image bands entered into the model as important variables in the classification; furthermore, vegetation indices were strongly important in discriminating between classes. Textural indices were not as important as other variables in the overall classification, but when left out of the model, there was little power in discriminating between dry deciduous and spiny forest.

Distance to river was the most important variable in the classification, which likely indicates the presence of an environmental gradient, such as soil moisture or soil type corresponding to this variable. Other variables of high importance were related to density of green vegetation, soil and leaf moisture, and forest biomass. The five variables of importance, after distance to river, were calculated solely from the July 07, 2006 dry season image. This suggests that there was a substantial difference in moisture and green vegetation between forest classes at that time of year. MSAVI2 responds to photosynthetic activity of vegetation; in study sites having areas of sparse vegetation, MSAVI2 outperforms the similar Normalized Difference Vegetation Index (NDVI) by minimizing soil background influences (Qi et al. 1994). The Greenness Transform also "capitalizes on differences in green vegetation between forest types with higher values

corresponding to higher biomass" (Jensen 2005), while the SRI "exploits differences in the spectral signature of plants and provides an indirect measure of leaf-area index" (Jordan 1969).

The VCI (also known as a mid-infrared to near-infrared ratio) is often used to aid in classification of vegetation following a fire as it performs well for mapping burns (Epting et al. 2005). In the context of this study, VCI is likely related both to small burn scars in the study area, as well as to desiccated vegetation and soil moisture (Miller and Yool 2002). IRI has been associated with plant biomass and seasonal foliage changes; in July 2006, there were significant differences in the foliage between forest classes and this index can help distinguish between them (Feeley et al. 2005).

Inclusion of field data on soil moisture and soil type in the model may improve the ability to separate forest classes. In addition, inclusion of field-collected variables such as tree basal area, tree height, and percent canopy opening may aid in separating heavily degraded forest from non-forest classes. Future work will also focus on identifying spectral and field variables that will help to identify transitions between forest classes.

In a comparison with previous land cover classifications available for the area, this study's classification of forest classes in and around BMSR is more useful for conservation planning. Not only is the spatial resolution improved, but vegetation classes are more representative of the area's forest diversity. This classifier is a promising method for mapping Madagascar's varied southern dry vegetation at even broader scales. Areas at the watershed level, and above could be mapped using freely available Landsat images from the U. S. Geological Survey. For planning at the ecoregional level, a

Random Forest classification using Moderate Resolution Imaging Spectroradiometer (MODIS) imagery at 500 m or 250 m resolution would provide better resolution maps than are some currently available map products, and with the use of MODIS Vegetation Index products, it is likely the forest classification would also be capable of distinguishing between spectrally similar dry forest classes. Finally, if only a single image can be procured for southern dry forest classification, data from this study suggest it should be from the dry season.

This classification is a useful tool for describing lemur habitat throughout the BMSR landscape. By overlaying lemur abundance onto this classification, we can begin to discern patterns in their distribution by forest class, instead of just by geographic location. With a forest cover classification, we can now move beyond lemur feeding-level microhabitat descriptions to home-range level macrohabitat descriptions. By examining macrohabitat patterns at broader scales—and outside of protected areas—we may see patterns not evident at the microhabitat level, and this may inform lemur studies at multiple habitat levels.

Scene ID	Date
ASTER Level 1B:	2004
AST_L1B_00311062004071608_20070122193656_32203	Nov. 6
ASTER Level 1B:	2005
AST_L1B_00302102005071628_20070122193505_28319	Feb. 10
ASTER Level 1B:	2005
AST_L1B_00303302005071650_20070122193457_27987	Mar 30
Landsat 7 (ETM+)	2006
Path 160 Row 76	July 7
ASTER Level 1B:	2006
AST_L1B_00309252006071643_20070122193608_30797	Sept. 25
ASTER DEM:	2006
AST14DEM_00309252006071643_20070118151915_25356	Sept. 25
Landsat 7 (ETM+)	2007
Path 160 Row 76	Sept. 28

Index	Abbv.	Formula	Reference	
Normalized Difference Vegetation Index	NDVI	(NIR-RED) / (NIR + RED)	(Pettorelli et al. 2005)	
Second Modified Soil Adjusted Vegetation Index	MSAVI2	(((2*NIR)+1)-(sqrt(((2*NIR)+1)^2 – ( 8*(NIR-RED))))) / 2	(Qi et al. 1994)	
Infrared Index (TM only) Mid-Infrared	IRI	(Band 4 - Band 5) / Band 4 + Band 5)	(Hardisky et al. 1983) (Musick and	
Index (TM only)	MIRI	Band 5 / Band 7	Pelletier 1986)	
Normalized Difference Senescence	NDSVI	(SWIR - RED) / (SWIR + RED)	(Ceccato et al. 2002)	
Soil Adjusted Total Vegetation Index (TM only)	SATVI	((Band 5 - Band 3) / (Band 5 + Band 3 + L)*(1+L))-Band 7/2	(Marsett et al. 2006)	
Simple Ratio Index	SRI	(Band 4 / Band3)	(Jordan 1969)	
Vegetation Condition Index (TM only)	VCI	Band 7/TM Band 4	(Sivanpillai et al. 2006)	

Table 2.2 Description of vegetation indices used in the classification.

Table 2.3 Confusion matrix for training data in Random Forest classification. Cell values in hectares.

Class	Gallary	Der	Spiny	NotForest	Total	User's
Class	Gallery	Dry	Spiny	Notrorest	Total	accuracy
Gallery	105	10	0	1	116	90.6%
Dry	5	169	9	11	194	87.2%
Spiny	0	20	41	4	65	63.1%
NotForest	0	9	0	77	86	89.5%
Total	110	208	50	93	461	
Producer's accuracy	94.5%	81.3%	82%	82.7%	85.1%	

Table 2.4 Matrix comparing predicted Random Forest forest class by percent study area with that of each of the four comparison maps. Values in parentheses represent percent agreement of forest classification with Random Forest classification. Cells without parentheses indicate no agreement with Random Forest classification.

	Random Forest Classification					
	Gallery	Dry	Spiny	Nonforest	% total of study area	
	11%	55%	25%	9%	100	
Comparison Maps						
Kew (Du Puy and Moat 1998)						
Deciduous dry forest and scrub	0%	28% (51%)	24% (96%)	7%	59	
Not forest	11%	28%	0%	2% (22%)	41	
IEFN (IEFN 1996)						
Dry or spiny forest	0%	35% 24% 8% 67 (74%)				
Agriculture	11%	20%	1%	1% (11%)	33	
Savannah w/o woody vegetation	0%	< 1%	0%	0%	< 1	
SPOT4 (Mayaux et al. 2000)						
Savannah	0%	38%	25%	7% (77%)	70	
Dry forest	11%	18% (32%)	0%	2%	31	
CEPF (Moat and Smith 2007)						
South west spiny forest thicket	3%	23% 24% 3% (59%)		53		
Degraded south west spiny forest	0%	<1%	<1% (<1%)	<1%	1	
Wooded grassland-bushland	<1% (<1%)	13%	1%	4% (44%)	17	
Plateau grassland-wooded grassland mosaic	0%	0%	0%	<1% (<1 %)	<1%	
Cultivation	7%	19%	0%	2% (22%)	29	



Figure 2.1 The study region at Beza Mahafaly Special Reserve



Figure 2.2 Sample locations of tree species sampling plots



Figure 2.3 Classification of forests in and around Beza Mahafaly Special Reserve



Figure 2.4 Random forest-based multi-dimensional scaling plot of forest classes.



Band 52 = Distance to River; Band 44 = MSAVI2, 07-2006; Band 38 = Greenness; Band 41 = SRI, 07-2006; Band 42 = VCI, 07-2006; Band 46 = IRI, 07-2006; Band 51 = Difference in MSAVI2 (09/2006-07/2006); Band 39 = Greenness 07-2006; Band 45 = DEM, 07-2006; Band 5 = Band 2, 02-2005; Band 4 = Band 1, 02-2005; Band 36 = IRI, 09-2007; Band 31 = Simple Ratio, 09-2007; Band 28 = Greenness, 09-2007; Band 40 = Thermal Infrared Radiance, 07-2006

Figure 2.5 Random forests variable importance plots of first 15 most important predictor variables forest classification.

# **Gallery Forest**



Figure 2.6 a) Partial dependence plots for distance to river.(A partial dependence plot gives a graphical depiction of the marginal effect of a variable on class probability.)





**Spiny Forest** 

Figure 2.6 a) (cont'd)



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**Not Forest** 

# **Gallery Forest**



Figure 2.6 b) Partial dependence plots of MSAVI2. (A partial dependence plot gives a graphical depiction of the marginal effect of a variable on class probability.)





Spiny Forest





**Dry Forest** 

Figure 2.6 b) (cont'd)



Not Forest

MSAVI2, July 2006

# **Gallery Forest**



Figure 2.6 c) Partial dependence plots for Greenness Transform. (A partial dependence plot gives a graphical depiction of the marginal effect of a variable on class probability.)

Figure 2.6 c) (cont'd)



**Spiny Forest** 

Grenness, July 2006

Figure 2.6 c) (cont'd)



Figure 2.6 c) (cont'd)



Not Forest

Grenness, July 2006



Figure 2.7 a) Remaining Primary Vegetation (Du Puy and Moat 1998)



Figure 2.7 b) Inventaire Ecologique Forestier National (IEFN 1996)


Figure 2.7 c) SPOT VEGETATION map (Vegetation Map of Madagascar) (Mayaux et al. 2000).



Figure 2.7 d) CEPF Vegetation Map (Moat and Smith 2007)

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# CHAPTER 3 - LEMURS IN A COMPLEX LANDSCAPE: MAPPING SPECIES DENSITY IN SUBTROPICAL DRY FORESTS OF SOUTHWESTERN MADAGASCAR USING DATA AT MULTIPLE LEVELS

#### Abstract

The study of southern dry forest lemurs has been largely restricted to small reserves, yet, the majority of the region's lemur populations reside outside of protected areas. *Lemur catta* and *Propithecus verreauxi* occupy the same forests but have different dietary preferences. This study assessed *L. catta* and *P. verreauxi* population densities across a 3 km dry forest gradient (1539 ha) in southern Madagascar. The study was designed to allow lemur densities to be related to particular forest classes. A particular aim of this study was to collect lemur data in both protected and unprotected areas.

Density estimates were calculated using point transect distance sampling in a study area that contained the Beza Mahafaly Special Reserve and adjacent disturbed forests. The highest densities recorded for each species were in the protected area where the two species were most segregated in their distribution, with catta density highest in gallery forest class, and *P. verreauxi* density highest in dry deciduous. Densities of both species varied widely outside of the protected area, but *P. verreauxi* density was more uniform than was *L. catta*. Results of this study indicate that patterns of lemur density in protected areas are not representative of patterns in disturbed forests; this also suggests that we cannot fully understand the ecological constraints facing primate species by studying them only in protected areas. This research highlights the value of pairing the study of landscape-level patterns of species distribution with both local ground-level

ecological interpretations and broad-scale satellite data; information from only one level may give an incomplete view of the community.

# Introduction

Madagascar is biogeographically diverse with a host of vegetation types supporting a rich lemur fauna. Forest loss in Madagascar is ubiquitous in all forest types, but, fortunately, rain forest and western dry forest lemur species enjoy protection in an array of reserves—both small and large—throughout their respective biogeographic regions. Despite the high plant endemism of southwestern Madagascar (Phillipson 1996), this region has a dearth of protected areas compared to other biogeographical regions in the country (Hannah et al. 2002, Moat and Smith 2007); its endangered subtropical dry forests have received comparably little consideration for lemur conservation, despite the fact that dry and spiny forest loss rates are equal to, or even higher than, Malagasy rain forests (Mittermeier et al. 1994, Harper et al. 2008).

Since President Marc Ravalomanana's 2003 announcement to triple the country's protected areas, the Malagasy Government has created 15 new protected areas (Lovgren 2007), including six new parks (Madagascar National Parks, Norris 2006). Two protected areas in southwestern Madagascar have been extended in size, including Tsimanampesotse National Park (Bradt 2007) and Beza Mahafaly Special Reserve (Raharimalala 2008), and a couple of community managed protected areas have been newly designated (Ministère de l'Environnement et des Forêts), but even with these additions, southwestern Madagascar still lags behind other regions in percent forest protected—less than 5% of southwestern dry deciduous and spiny forest vs. nearly 40% for humid forest (Moat and Smith 2007).

As the only two diurnal lemurs in Madagascar's southern forests, ring-tailed lemur (*Lemur catta*) and Verreaux's sifaka (*Propithecus verreauxi*) are the region's

flagship species (Durbin 1999, Walpole and Leader-Williams 2002, Jolly 2003b) charismatic symbols of the ecosystem that serve to stimulate conservation awareness in the region (Hawksworth et al. 1995, Simberloff 1998). Both taxa are endemic to southern Madagascar (Mittermeier et al. 2006), and while their geographic ranges overlap, there are significant gaps in our knowledge of their respective distributions. With so little of this region's forests protected, a large proportion of the two species' populations must, therefore, live in unprotected forests.

The dry forests of inland southern Madagascar consist of three forest classes: gallery (or riverine), dry deciduous, and spiny. When all three forest classes are found in a single landscape, these forests are typically arranged along a moisture gradient with gallery located along river courses, spiny situated most distant from the river, and dry deciduous positioned in between. Both lemur species are known to utilize all three forest classes to some extent. Efforts to implement conservation measures for the two lemur species have been hampered by both an absence of forest classification maps representing the diversity of vegetation classes at local and landscape-level scales, and a lack of understanding of how lemurs utilize multiple forest classes.

Both lemurs are well-studied in the protected forests of Beza Mahafaly Special Reserve (BMSR) and Berenty Private Reserve (Sussman 1991, Gould et al. 1999, Sauther et al. 1999, Brockman et al. 2001, Richard et al. 2002, Yamashita 2002, Gould et al. 2003), but there are still comparably few studies on lemur populations inhabiting forested areas outside of these small, roughly 100 ha protected parcels of mixed dry deciduous and gallery forest. Consequently, our current understanding of both *L. catta* and *P. verreauxi* (hereafter referred to as catta and sifaka, respectively) is based primarily on

studies conducted in protected gallery forests, which experience minimal anthropogenic impacts (Richard et al. 1993, Jolly and Pride 1999, Jolly et al. 2002, Gould et al. 2003). Still, the vast majority of forests in the southwest are at risk of degradation from such threats as livestock grazing, fuelwood collection, agricultural conversion, and mining activities (Sussman and Rakotozafy 1994, Fenn 2003).

Simultaneous sampling of the two sympatric lemur species has been rare, apart from at Berenty Reserve where both lemurs have been censused at sporadic intervals since the early 1960s (Jolly 1972, Jolly and Pride 1999, Norscia and Palagi 2008). Simultaneous sampling took place in 1970, when Jolly (1972) re-censused both species in a 10-ha study area of gallery forest; however, no comparisons were made between densities of the two species. Presumably the data are statistically comparable, but the intent of the study was to assess changes in troop size and troop spacing behavior. In 1981, both species were censused in the Malaza portion (94 ha) of Berenty Reserve. Multiple researchers used both spot-check and continuous count methods until consistent troop numbers and composition were reached; however, only that fraction of the sifaka population ranging along forest paths could be recorded because animals were skittish. In addition, researchers noted that the accuracy of the counts may have been affected by differences in lemur detectability by vegetation class (Howarth et al. 1986). These studies illustrate some of the difficulties in making inferences about lemur density in areas consisting of multiple vegetation classes. Surveys in small areas characterized by a single forest class, may not be representative of populations in other areas of the same forest class. And unless one can be sure that a complete census has been achieved, differences in detectability should be accounted for. The sampling design used in the

Berenty studies discussed above limits the ability to make statistically significant species density comparisons by habitat. Furthermore, we are precluded from comparing density estimates obtained in single species studies because they were obtained using a variety of sampling methods, at different times of the year, and often in different locations (typically in different reserves). Consequently, the vast majority of published density estimates for both lemur species do not extend beyond protected, and largely habituated, populations (Richard et al. 1991, Sussman 1991, Jolly and Pride 1999, Brockman et al. 2001, Koyama et al. 2001, Yamashita 2002, Gould et al. 2003, Mertl-Millhollen et al. 2003, Simmen et al. 2003).

This is a comparative study of the spatial distribution of catta and sifaka in three forest classes in and around the Beza Mahafaly Special Reserve. It combines a landscapelevel model of species density and distribution with both fine-scale ecological forest observations and broad-scale satellite spectral data, in order to elucidate patterns that may otherwise be obscured at just a single level (Maurer 1999). The study area was classified by vegetation class, and lemur density was estimated during the dry season using distance sampling methods (Buckland et al. 2001). Lemur density was then compared by species, protection status, and forest class. Studies such as this are vital to conservation planning efforts, as effective conservation planning depends on availability of data about populations living in varied habitats.

#### Methods

#### Study Area

The Beza Mahafaly study area is described in Chapter 1. The land cover of the study area was classified into four classes (gallery forest, dry deciduous forest, spiny

forest, and not forest) using a "random forest" classification algorithm described in Chapter 2. As calculated from the classified image of the region, the study area (BMSR and surrounding area) consisted mostly of dry deciduous forest (55%), followed by spiny forest (25%), gallery forest (11%), and non-forest (9%) (Figure 3.1). The largest area of intact (undisturbed and unbroken) forest was found in Parcel I. Parcel II contained the majority of spiny forest in the study area. Dry deciduous and spiny forests dominated the western half of the study area; the majority of non-forested lands were found there, as well. Non-forested lands consisted of either bare soil, grasslands, woodlands with sparse tree cover, bushland, and/or agricultural fields.

# Field Measurements

The study area was divided into nine sampling regions based on reserve boundaries, roads, and forest classes (see Figure 3.1). Sampling regions ranged in area from 19 ha to 528 ha, with smaller areas in and around Parcel I and the rest in and around Parcel II. A triangular point array sampling grid of 404 points, with a random start location, was overlaid on a map of the study area (see Figure 3.1) to identify locations where lemur counts were to be made. The distances between points on the grid varied between 115 m in gallery forest and 300 m in spiny forest, with sampling points placed in proportion to lemur density (i.e., more samples in areas believed to have higher density) to reduce variance and confidence intervals of the final estimate (Strindberg et al. 2004).

Distance sampling was chosen as the estimation method because it is a method that can account for differences in lemur detectability due to such factors as habitat class, weather condition, observer, etc.(Buckland et al. 2001). The distance from each sampling point to the lemur group is recorded and used to estimate the "detection function", which describes the probability of detecting a lemur group as a function of distance from the observer. Reliable estimates of abundance and density from distance sampling depend on meeting the conditions of three assumptions: (1) all individuals at the sampling point are detected; (2) all individuals are detected at their initial location (e.g.; no evasive movements before detection); and (3) all distances are measured accurately (Buckland et al. 2001). Sampling methods were designed to meet these assumptions.

Distance sampling can be performed using either line or point transects (*sensu* (Buckland et al. 2001)); point sampling was chosen since it has an advantage over line transect sampling when sampling for multiple species in patchy habitats, especially when habitat data are also being collected (Buckland et al. 2001). In addition, point sampling allows more time for observers to detect and locate animals and this can be advantageous when sampling arboreal groups that may be feeding or sleeping; point samples were especially useful in the dry season as many groups were detected when heard feeding in the dry vegetation. Point samples are independent sampling units when they are systematically spaced such that spacing between lines of points is equal to spacing between successive points along lines; points established along transect lines in which points are not evenly spaced across a region are a form of cluster sampling (Strindberg et al. 2004).

Both catta and sifaka are social primates, therefore data were collected on lemur groups, rather than on individuals, in order to meet the assumption of sighting independence. Double-counting of moving groups is not problematic when using point samples provided that detections are independent of each other (i.e., animals are not

"herded" by observers to subsequent points). Repeated observations of the same group (i.e., double-counting) will not violate the assumption of independence, so long as groups are not detected more than once from the same point (Rosenstock et al. 2002). In the case of lemurs, this is easy to ensure.

Point samples used to estimate lemur density were sampled twice, once during the period June-July 2006, and again June-August 2007. Each point sample equals a single unit of effort. Sampling was conducted during the dry season when detectability of lemurs was improved by some tree species being in leaf-off condition (Ratsirarson et al. 2001) and by the ability to hear lemurs moving through, and feeding on dry vegetation. All sampling was conducted between 0800 - 1130 and 1300 - 1630 at times without rain or excessive wind. All point samples were accessed on foot, and approximately 10 points were sampled per day. Each day was divided into two sampling sessions, morning and afternoon. On a little more than half the days, we sampled within the same region during both sessions. Within each sampling session, we typically sampled a set of points within the same area of the region. Time between sampling points varied according to distance between points and presence of lemur groups, but generally, 30 minutes passed between point samples.

Observers were trained in the method and all worked together at each sampling location. Each of the four observers in the team played a specific role in lemur sampling. I collected locations of the lemur groups using a Global Positioning System (GPS) and served as recorder of all information, while another was responsible for collecting distances with the laser range finder. Meanwhile, the two other members of the team

counted the number of individuals in the group; if the group fled before all members were counted, they both followed the group to obtain the group size.

On arrival at the point sample, observers waited approximately two minutes before beginning the five minute sampling period. Counts of all individuals in each lemur group (known as clusters in distance sampling sensu (Buckland et al. 2001)) were conducted for five minutes at each sampling point; infants born in the sampling season were not included in group counts. On rare occasions, multiple groups of a single species were detected from the same point, but individuals of each group were easily differentiated due to distance between them except in two cases. These instances involved altercations between groups, and in each case, groups were followed after they dispersed and individuals of each were counted. To the best of our knowledge, groups represent social groups.

Observations from 2006 and 2007 were pooled for analysis. Detection distances (required to model the detection function under the distance sampling methodology) were estimated for all observations using one of two methods: (1) when groups could be visualized from the sampling location, the horizontal distance to the group was determined using a laser ranger finder, and (2) in those cases where the group was heard, but not seen, from the sampling location, the group was located and its coordinates were recorded using a Garmin V GPS fitted with an external antenna (GPS Outfitters Titan III) and detection distances were later calculated in a geographic information system (GIS) using ArcView 3.2 (Environmental Systems Research Incorporated).

# Lemur Groups

Group size detected per point sample was mapped where lemurs were detected. If lemurs were detected at a sampling point in both field seasons, group size was averaged. Unequal variance t-tests (Ruxton 2006) were used to test for differences in group size between species, as well as for differences in group size of each species by forest class (for dry deciduous versus gallery forest only, as too few lemur groups were sighted from spiny forest sampling points to include all three forest classes in this comparison). Each data point represents a sighting of a single group.

### Lemur Density Estimates within Mixed-Forest Sampling Regions

Given that very few large patches of any single forest class remain in the study area, it is useful to examine the patterns of species distribution by mixed-forest regions. Lemur density was estimated in sampling regions comprising multiple forest classes in order to make comparisons between specific areas in the study area.

To estimate lemur density, first, a detection function was fit to the observed distances between observer and lemur group (i.e., the distance between observer at the sample point location and the lemur group location). The proportion of lemurs missed on the survey within the truncation distance (i.e., the distance beyond which data were excluded from analysis) can then be estimated; this represents the probability of detection, p. Lastly, the estimate of lemur density is adjusted (upwards) for p to account for the proportion of the population that was undetected at the point samples. For a good overview of the method see Thomas et al. (2002), and for details of its use and analysis consult Buckland et al. (2001).

Density and probability of detection were estimated using the computer software DISTANCE 5.0 (Thomas et al. 2006). One-way analysis of variance tests were used to

test for differences in distance-to-groups (i.e., lemur detectability) by species, habitat, time of day, year, and group size. Final models were selected using Akaike's Information Criterion (AIC) (Burnham and Anderson 2002). Paired-tests for differences by sampling area in density, both between, and within, lemur species were performed using a z-test approximation of Satthewaithe's Approximation (Thomas et al. 2006). *Lemur Plot Density Estimates within Forest Classes* 

In order to compare lemur density by forest class, estimates of lemur density were also calculated for dry deciduous and gallery forest classes, as shown in Figure 3.1. (There were insufficient data to calculate density for spiny forest). Here, it was necessary to calculate a single "plot density" for each sampling point since points were located in sampling regions characterized by multiple forest classes. In this context, "plot density" was defined as lemur abundance per area forest class. To calculate lemur abundance, lemur counts at each point sample were adjusted for probability of detection. Plot area was then calculated by dividing the area of each forest class by the number of sampling points located within it. Lemur abundance was then divided by plot area to calculate lemur plot density. To calculate biomass/ha, biomass of catta was based on average adult weight at BMSR of 2.211 kg (Sussman 1991), and biomass of sifaka was based on average adult weight at BMSR of 2.8 kg (Richard et al. 2000).

Tests for differences in plot densities of lemur species among different forest classes, as well as between protected and unprotected parts of the study area, were performed using three generalized linear models to account for an overabundance of zeros in the data and the resulting over-dispersion (i.e., a higher than expected variance). The three candidate models identified included (1) a simple negative binomial model

(NB) with a log link function, (2) a zero-inflated Poisson model (ZIP), and (3) a zeroinflated negative binomial model (ZINB) (Martin et al. 2005, Potts and Elith 2006, Sileshi 2008). Vuong tests and likelihood ratio tests were used to select the best candidate model (Vuong 1989). All models were fit in R using the zeroinfl() function from the pscl package (Zeileis et al. 2007, R Development Core Team 2008).

This research complied with protocols approved by Michigan State University Institutional Animal Care and Use Committee and adhered to the legal requirements of Madagascar's Association Nationale pour la Gestation et Aires Protégées.

## Results

#### Lemur Groups

There were nearly twice as many sifaka group detections (n=102) as there were catta group detections (n=56), but catta groups were significantly larger than those of sifaka (t = 08.16, P < 0.001, d.f. = 80) (Table 3.1, Figures 3.2a and 3.2b). Mean group size of catta was 9.5 lemurs, and there was no significant difference in mean group size between gallery (8.99) and dry deciduous forest (10.36) (t = 1.46 P = 0.15 d.f. = 39) (Table 3.1). However, the majority of largest catta groups (71%), 13-20 animals, were detected outside of the reserve in the dry deciduous forest of Region 7. Of the 9 catta groups in Region 7, five contained greater than the average catta group size of  $\geq 13$  animals sensu (Gould et al. 2003). In contrast, only two of the 45 groups in Regions 1-6 contained  $\geq 13$  animals. Mean group size of sifaka was 5.44 lemurs, and group size was significantly larger in dry deciduous forest (5.71) than in gallery forest (4.87) (t = 1.98, P = 0.05, d.f. = 95). (Table 3.1). The distribution of catta in the study area was more

restricted and clustered than that of sifaka; catta groups were most clustered in the interior portion of protected gallery forest (Figures 3.2a and 3.2b).

## Lemur Density Estimates within Mixed-Forest Regions

Lemur detectability varied by both species and habitat, but there was no difference in lemur detectability by time of day, year, or group size. Catta and sifaka densities were not significantly different within the six regions located closest to the river (Regions 1-6); yet, sifaka density was significantly higher than that of catta in the drier western region (Regions 7 and 8) (Table 3.2, Figure 3.1). Catta density was higher in regions located along the Sakamena River (Regions 1-3) than in others (Table 3.3a, Figure 3.1), and catta were absent from Parcel II, the driest part of the study area. Catta density was highest in the eastern region of Parcel I (Region 2), comprising mainly protected gallery forest, and catta density decreased with distance from the Sakamena River (Figure 3.3). Sifaka density was fairly uniform across the study area except for 1) notable low density in Region 4, unprotected dry deciduous forest adjacent to intact gallery forest, and 2) high density in the mostly dry deciduous western regions of Parcel I (Region 5) (Table 3.3b, Figure 3.3).

Only four total observations were made at point samples in Region 9, and all were sifaka; therefore, these data were excluded from the analysis, since the detection function could not reliably be modeled in an area of that size (427 ha) using only four data points. However, sifaka groups were detected between point sample transects in spiny forest, and reserve staff camped in Parcel II frequently observed sifaka groups in nearby spiny forest at the southern edge of the parcel. Despite their low density, sifaka are considered permanent residents in this spiny forest by reserve staff who frequent the forest. While

no catta were observed from point samples in Region 9, signs of catta presence there included feces, footprints, and a skull.

#### Lemur Plot Density Estimates within Forest Classes

Vuong tests indicated that a zero-inflated negative binomial model (ZINB) was the best of the candidate models, and only those results are presented here. Across the study area, catta plot density was significantly higher in gallery forest than that in dry deciduous forest (Table 3.4). Sifaka plot density was also significantly higher in gallery forest than in dry deciduous forest (Table 3.4).

Catta attained much higher plot densities (1-34 lemurs/ha) than did sifaka (1-17 lemurs/ha) (Figure 3.4); when body weight of individuals is accounted for, catta plot biomass is estimated 2.2 -75.1 kg/ha while sifaka is 2.8 - 47.6 kg/ha. Catta plot densities were higher in gallery forest than in dry deciduous forest (Table 3.4), and they generally decreased westwards across the study area to their lowest in the southwestern dry deciduous forests (Figure 3.4). Concentrations of catta detections, coupled with high plot densities accounted for high density in gallery forest. Catta density was highest in the northeast corner of Parcel I—the core area of protected gallery forest, but it was also high in gallery-dry deciduous forest transition areas near the reserve camp. Outside of gallery forests, catta were often detected in the vicinity of patches of gallery forest.

While sifaka plot density was higher in gallery forest than in dry deciduous forest across the study area, sifaka plot density was highest in protected dry deciduous forest due to the large number of detections there (2.32 lemurs/ha). As was the case with catta, the majority of sifaka detections were in dry deciduous and gallery forests near the river

(Figure 3.4). Sifaka plot density was remarkably uniform across forest classes (4-11 lemurs/ha at nearly 70% of all sample points where sifaka were detected).

Given that the vast majority of studies conducted on these two species have been in gallery and dry deciduous forests within 1 km of a river (Sussman 1991, Jolly and Pride 1999, Sauther et al. 1999, Richard et al. 2002), we felt it important to compare density by forest class and protection status in forests within 1 km of the Sakamena River (Regions 1-6). There was a significant three-way interaction between forest class, species, and protection status, with catta in protected gallery forest having the highest density, followed closely by sifaka in protected dry deciduous forests (Figure 3.5). Within the protected area, sifaka plot density was lower in gallery than in dry deciduous forest, while catta plot density was higher in gallery and lower in dry deciduous forest. This pattern was not observed in disturbed forests directly adjacent to Parcel 1, as the two species' densities in these areas were not significantly different by forest class (Figure 3.5).

In summary, both species were found in highest densities in Parcel I, and densities of both species were comparably lower in Parcel II, than in other areas. Sifaka density was higher in dry deciduous forests than that of catta. Catta density was not significantly higher than sifaka in gallery forest. Neither species attained high density in spiny forest, although sifaka density was higher than that of Catta.

## Discussion

#### Lemur Groups

Group size varies widely across primate species and even within some species. While there are individual benefits to living in social groups (e.g., foraging advantages,

predator avoidance, and cooperative defense against conspecifics), there are also significant disadvantages to group-living, namely feeding competition (Chapman and Chapman 2000). While there was no statistical difference in catta group size between gallery and dry deciduous forest classes, evidence suggests there may be different determinants of group size at play within these two forest classes.

At Berenty Reserve, Pride (Pride 2005) found that optimal catta group size was "intermediate" and that lemurs in small and large groups experienced greater levels of stress, as indicated by elevated cortisol levels. He also found that Berenty's larger groups were found only in areas where intergroup conflicts over food resources were high. He speculated that members of large groups were stressed during the harsh season because their food resources were indefensible against other groups, but their group size was optimized over the long-term.

At Beza Mahafaly Special Reserve, large catta groups ( $\geq$  13), were found in both gallery and dry deciduous forest. Large groups in gallery forest were located in areas with both a high density of tamarind trees and a high density of conspecifics (2.7-3.6 lemurs/ha) and appear to be "optimized" just as those at Berenty, described in Pride (2005); that is, catta in large groups may benefit so greatly from their group size in high food abundance areas for the majority of the year, that they are willing to incur high costs of group membership during the harsh dry season. In addition to foraging advantages, large group size in gallery forest may also bestow greater protection to individuals against threats from conspecifics.

On the other hand, the only large catta groups observed in dry deciduous forests were located on the west side of the study area (Region 7), well away from the gallery

forests along the river in areas with low, if any, density of tamarind trees and low density of conspecifics (~0.5/ha). While the dry deciduous forests of Region 7 are spectrally similar to those of Regions 4-6, overall the forest canopy of Region 7 is much more open than that in Regions 4-6. In this region, intragroup competition for food resources is expected to be high, whereas intergroup competition for food is expected to be low. With low lemur density, food resources in this region may be easy to defend; however, travel time may be increased due to large areas of nonforested land which may expose individuals to higher hawk predation pressure.

In addition, predation pressure by dogs is certainly higher in this region than at Berenty which is well-patrolled and frequented by many tourists (Pride 2005); and it is also likely to be higher than in Parcel I of BMSR. We encountered wild dogs in this region on multiple occasions (and once we were charged by a wild dog pack), but we encountered none in the east (although a dog attack on an juvenile catta was documented by another researcher in Parcel I during this study in 2006). Large group size in dry deciduous forest may bestow foraging advantages, as well as greater protection against predators. In cases like this with easy food patch defensibility and/or high predation pressure, large groups may be favorable (Van Schaik 1983).

Sifaka group size was higher in dry deciduous forest than in gallery, and groups were well-distributed throughout all but the driest portion of the study area. Richard and Heimbuck (1975) found that sifaka territories often overlap, and the spatial arrangement of sifaka groups in this study, especially in protected dry deciduous forest, supports their finding. Consequently, increased intergroup interactions would be expected in deciduous dry forest. Larger group sizes may allow sifaka to defend food patches, especially those

that are only seasonally available. However, with information emerging about the incidence of infanticide in the species (Lewis et al. 2003, Littlefield 2010), large group size may also provide greater protection for infants from males who regularly transfer between groups (Richard et al. 2002).

#### Catta and sifaka more segregated in protected habitat

The two lemur species differed in distribution of plot densities across the study area; while sifaka plot density was fairly uniform across forest classes, Catta plot density declined across the forest gradient from the river westwards to the spiny forest. This decline in Catta plot density may be related to the decrease in gallery forest moving west along the gradient. The distribution of sifaka throughout the study area was relatively uniform across forest classes, although plot density was highest at gallery-dry deciduous boundaries. High sifaka density in protected deciduous and unprotected gallery suggests there may be similarities in forest structure and composition to which sifaka respond. Furthermore, gaps or edges may contain high-quality food resources for lemurs (Ganzhorn 1995, Lehman 2006), and presence of numerous edges between gallery and deciduous dry forests may also explain high sifaka plot densities in protected dry deciduous and disturbed gallery forests.

Outside of protected areas, there was quite a bit of overlap in species plot density, while there was much less species overlap in protected areas. This suggests there may be different mechanisms behind the coexistence of these two species depending on forest protection status. Outside of protected areas, both species were often spotted feeding in close proximity to one another. Perhaps the open canopy allows for a greater diversity of tree species diversity which accommodates the food preferences of both species, and

thereby allows for greater food partitioning. Or perhaps, multiple groups foraging together may increase detection of predators. In protected areas, there appears to be some degree of spatial partitioning suggesting that multi-species group foraging may not be as beneficial there. It is not clear if differences in spatial patterns of distribution between protected and unprotected areas can be explained by food partitioning and corresponding habitat characteristics, so future work should address the mechanisms producing these patterns.

## Catta density high in gallery forest regardless of status

Catta plot density was much higher in gallery forest than in dry deciduous forest, and this corresponds with previous observations summarized in Sussman et al. (2006). Yet, catta presence in dry deciduous forest does not appear to be an anomaly, as they were detected at numerous locations in dry deciduous forest at distances of up to 3 km from the Sakamena River.

Some have speculated that catta predilection for *T. indica* (Gould 2006), the dominant tree species in gallery forest, is responsible for high catta density in that habitat, since there is often the expectation that population density is positively correlated with habitat preference (Fretwell 1972, Cody 1985). There is, in fact, strong evidence to support the idea that gallery forest is the preferred catta habitat (Gould 2006), as even in regions characterized by mostly dry deciduous forest, many catta groups were located in close proximity to patches of gallery forest, some of very small size (< 1 ha).

Given that catta density declines with distance from the river, we should consider that their density may be correlated with some environmental gradient (e.g., soil moisture, foliar moisture), either directly or indirectly. *Tamarindus indica* density also

declines with distance to the river (Sussman and Ratsirarson 2006). Mertl-Milhollen et al. (2006) investigated tamarind resources in relation to proximity to water at Berenty Private Reserve, a forest very similar in composition to BMSR, and found that water and nitrogen content of mature tamarind leaves available during the catta birth season (the dry season) were significantly correlated with proximity to the river, while fruit abundance was not. They also reported that catta foraging was correlated with tamarind leaf water and protein content, suggesting that catta may be selecting for tamarind leaves of a certain condition.

Despite the fact that *T. indica*, a gallery species, represents an important element of the catta diet (Sauther 1998, Yamashita 2002), catta density still may not correlate with high-quality habitat. In fact, their density may not reflect habitat preference or be positively correlated with fitness (van Horne 1983, Pulliam 1988). Without actual survival and fitness data we cannot assume that gallery forest is the highest quality habitat for catta at BMSR. However, there are some related survival data that may provide further insight into the issue.

Both Jolly et al. (2002) and Koyama et al. (2001) described differential survival of catta infants at Berenty Private Reserve. Mean 1-year infant mortality was 32.5-37.0% in gallery forest adjacent to tourist areas (with food and water provisions), while it was higher than 50% in dry deciduous forest (Jolly 2003a). Gould et al. (2003) reported a similar mean infant mortality (52%) at BMSR. Catta appear to benefit from food and water provisioning by people. We have observed individuals and groups raiding crops, scavenging trash, stealing food from kitchens, and drinking from myriad anthropogenic

water sources, and documented their presence in high density along the southern edge of Parcel I near camp.

Tourist and camp facilities are located close to gallery forest at both BMSR and Berenty. Purposeful food provisioning by tourists at Berenty was common until the practice was banned in 1999 (Pinkus et al. 2006); water provisioning for lemurs in forest troughs continues there today. Catta at Berenty still manage to obtain food by stealing and trash-raiding. In recent years, catta at BMSR have also begun raiding trash cans and stealing unattended pieces of fruit; frequently, they can be seen drinking water out of pails in camp. So, do higher-quality food resources (i.e., gallery forest) bestow higher fitness on gallery groups such that they have a competitive advantage at securing anthropogenic resources? Or do gallery groups simply benefit by their spatial proximity to anthropogenic resources? The question remains, whether high catta density in gallery forest is due to proximity to human-provided resources (unintended food and water provisioning), or due to reasons unrelated to human presence.

## Conclusion

Lemur density estimates from protected gallery forests from this study are in line with other published estimates (Jolly et al. 1982, Sussman 1991, Jolly and Pride 1999, Gould 2006); however, results from sampling multiple forest classes of different protection status suggest that there is disparity between lemur density in protected areas and disturbed forests, as well as across forest classes.

If one were to generalize density results obtained from protected forests to unprotected forests, both sifaka and catta density would be overestimated. The good news is that our data show that both species occupy unprotected areas, sometimes at even

higher densities than protected areas; but in the absence of data on survivorship and fecundity, we cannot eliminate the possibility that unprotected areas are acting as ecological sinks—very low quality habitat unable to support a population on its own that persists due to individuals immigrating from high quality habitat (Pulliam 1988).

Results from this study indicate that information collected on populations in protected gallery forest may not be representative of populations living either in unprotected gallery forest or in dry deciduous forest. There is no doubt that long-term studies on protected populations have provided us with invaluable information on both species' ecology and behavior, but it is important that some researchers move beyond the protected populations and collect information on groups living in forests more representative of the two populations as a whole. Without this information we cannot fully understand species requirements for the large majority of remaining populations of these two species, and we cannot hope to design effective conservation plans.
Groups	Catta	Sifaka
Number	56	102
Minimum	2	1
Maximum	20	11
Mean	9.50	5.44
Standard		
Deviation	3.37	2.18
Gallery		
Forest	8.99	4.87
Dry		
Forest	10.36	5.71

Table 3.1 Comparison of catta and sifaka groups

Comparison	Catt	a	Sifal	ka	Z statistic	Р
	Density (lemurs/ha)	Standard Error	Density (lemurs/ha)	Standard Error		
Regions 1- 6	2.16	0.82	2.33	0.67	0.16	0.87
Regions 7 & 8	0.36	0.19	1.99	0.49	-3.08	< 0.001

Table 3.2 Comparison of catta and sifaka density by mixed-forest sampling regions illustrated in Figure 1. Paired-tests for differences in density by region were performed using a z-test approximation of Satthewaithe's Approximation.

Table 3.3a) Distance analysis results by region for *L. catta*. The number of groups is after truncation of data to improve goodness-offit for detection function modeling in DISTANCE software. Density = lemurs/ha. Region numbers refer to regions identified in Fig. 3.1.

Region	Area	Gallery	Dry	Spiny	Samples	Total	Groups	Avg Group	Probability	Density (lemurs/ha)			ha)
								Size	of		CV		
	(ha)	(%)	(%)	(%)	(no.)	Effort	(no.)	(%CV)	Detection	Estimate	(%)	df	95 % CI
1	95	89	8	0	60	120	17	9.0 (10.0)	0.36	2.7	30	56	1.5 4.9
2	57	81	18	0	53	106	18	9.7 (7.6)	0.36	3.6	28	58	2.0 6.2
3	45	56	38	0	31	62	9	7.0 (16.0)	0.36	2.2	39	21	1.0 4.9
4	33	5	92	2	21	42	1	7.0 (0.0)	0.36	0.2	100	16	0.0 0.5
5	31	13	87	0	27	54	6	8.5 (8.5)	0.36	0.8	46	18	0.3 1.9
6	19	4	95	0	12	24	1	11.0 (0.0)	0.36	0.5	100	16	0.1 2.7
7	528	0	83	2	89	178	8	13.3 (9.1)	0.36	0.5	41	22	0.2 1.2
8	304	0	80	9	53	106	1	0.0		*			
9	427	0	14	81	58	116	0	0.0		0.0			

\* Too few observations to calculate given the size of the region. CV= coefficient of variation, CI=confidence interval, df=degrees of freedom

Table 3.3 b) Distance analysis results by region for *P. verreauxi*. The number of groups is after truncation of data to improve goodness-of-fit for detection function modeling in DISTANCE software. Density = lemurs/ha. Region numbers refer to areas identified in Fig. 3.1.

Region	Area	Gallery	Dry	Spiny	Samples	Total	Groups	Avg Group	Probability	Density (lemurs/ha)				
								Size	of		CV			
	(ha)	(%)	(%)	(%)	(no.)	Effort	(no.)	(%CV)	Detection	Estimate	(%)	df	95 %	6 CI
1	95	89	8	0	60	120	30	4.8 (8.1)	0.34	2.6	23	78	1.6	4.0
2	57	81	18	0	53	106	8	4.8 (10.8)	0.34	2.1	27	52	1.2	3.5
3	45	56	38	0	31	62	12	5.9 (10.3)	0.34	2.7	32	36	1.4	5.2
4	33	5	92	2	21	42	2	6.0 (0.0)	0.34	0.7	71	82	0.2	2.4
5	31	13	87	0	27	54	15	5.5 (8.7)	0.34	3.3	30	37	1.8	5.9
6	19	4	95	0	12	24	6	3.6 (23.0)	0.34	2.2	48	7	0.7	6.4
7	528	0	83	2	89	178	21	5.8 (8.7)	0.19	2.0	29	46	1.1	3.5
8	304	0	80	9	53	106	13	5.5 (12.0)	0.19	2.0	34	42	1.0	3.9
9	427	0	14	81	58	116	4	8.0 (13.5)		*				

\* Too few observations to calculate given the size of the region. CV= coefficient of variation, CI=confidence interval, df=degrees of freedom

Table 3.4 Comparison of lemur plot density by fo	orest class
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Species	Dry For	est	Gallery F	orest	Z statistic	р
	Plot Density Std.		Plot Density	Std.		
	(lemurs/ha)	Error	(lemurs/ha)	Error		
Catta	1.86	0.14	2.44	0.17	3.38	< 0.001
Sifaka	1.59	0.09	1.88	0.13	2.19	0.03



Figure 3.1 Study area shown with forest classification derived from a random forest classifier and sampling regions overlaid on point samples.



Figure 3.2 a) Catta group size at sample points. Dot size is proportional to number of individuals in group.



Figure 3.2 b) Sifaka group size at sample points. Dot size is proportional to number of individuals in group.



Figure 3.3 Correlation between lemur density and distance to the river including corresponding forest class.



Figure 3.4 Catta and sifaka plot density at each sample point, adjusted for probability of detection. Dot size is proportional to density



Figure 3.5 Mean lemur plot density estimates by forest class in protected and unprotected in forest located within 1 km from the Sakamena River. Vertical segments extend over  $\pm 1$  standard error. (Significant three-way interaction between forest class, species, and protected area status (Z= -0.909, *P*=0.03).

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# CHAPTER 4 - LEMUR-LIVESTOCK INTERACTIONS IN SUBTROPICAL DRY FORESTS

## Abstract

Livestock play an important role in society in southern Madagascar. Grazing strategies have shifted in recent decades, often resulting in the concentration of negative environmental impacts. Forest grazing activities have raised the concern of conservationists for the condition of primary habitat for the region's celebrated lemurs, *Lemur catta* and *Propithecus verreauxi*. The primate-livestock issue in the dry forests of southern Madagascar is a fairly unique case of wildlife-livestock interaction, and there has been little research on the issue.

Goals of this preliminary investigation into the effects of grazing activities on the region's forests included 1) characterization and comparison of forest structural parameters in adjacent grazed and ungrazed forest sites, and 2) comparison of lemur density in grazed and ungrazed forest sites. Grazing impacts on forest structural parameters appear to be more pronounced in the dry forest than in gallery, as reflected in tree basal area and especially, species composition. Differences between grazed and ungrazed gallery forest were reflected primarily in plant species composition. There was no significant difference in either lemur species' densities between the entire grazed and the ungrazed sites; however, comparisons by forest class captured differences that otherwise would have gone undetected.

*L. catta* density was unchanged between grazed and ungrazed sites, but *P. verreauxi* density decreased in grazed dry forests. Results suggest that grazing activities that do not significantly alter forest structure may support lemur densities similar to those

in ungrazed areas. However, *P. verreauxi*, in particular, seems sensitive to changes in forest structure in their preferred habitat.

"Madagascar could be saved if all the cattle and herders just left the island"

Spoken by an ornithologist (Kaufmann and Tsirahamba 2006).

## Introduction

If the lemur serves as the charismatic representation of Madagascar's "hotspot" biodiversity, then the Malagasy peasant represents the destructive force responsible for its habitat loss. Descriptions of Madagascar's biodiversity crisis often invoke images of a united front of peasant warriors laying waste to the country's natural resources.

The forests of southern Madagascar are little protected (Moat and Smith 2007), and forest loss here is largely attributed to agro-pastoralists' appropriation and development of land (Durbin et al. 2003). Livestock, in particular, are targeted by conservationists as a threat to biodiversity—they are blamed for forest loss, transportation of exotic grasses, degraded soils (Kaufmann and Tsirahamba 2006) and desertification (Jolly and Jolly 1984). According to one plant scientist, "the highly endemic forests of Madagascar are threatened with extinction by the raising of zebu." (Spichiger et al. 2004).

Livestock arrived in Madagascar in the 16<sup>th</sup> century (Ribot 1985), and livestock herds have been prolific in Madagascar for years (Morat 1973). In 2000, 65% of all Malagasy households derived their living from livestock, accounting for 15% of the country's agricultural GDP (with the majority of large-scale husbandry occurring in the more arid western and southern regions) (Kaufmann and Tsirahamba 2006). Indeed, today, livestock is the primary agricultural activity in the south (Fenn 2003).

Cattle are the most important asset in the lives of the southern Mahafaly and Antandroy peoples; they play multiple roles in society acting as stores of wealth,

commodities, labor, units of production, and social capital. Livestock also play a role in the principal events of life such as circumcision, marriage (including polygamy), and death. Cattle are treated less as a resource than as an apparent richness that ultimately determines an individual's position or "prestige" in society (Frére 1958).

In the past century, pastoralists in southern Madagascar have adopted less mobile herding strategies in response to outside forces such as cattle rustling, lost grazing lands, and development projects. Traditionally, many southern pastoralists practiced *midada*, a strategy in which livestock roamed freely in the forest unaccompanied by a herder. Mobile pastoralist strategies such as *midada* may be ecologically healthier approaches to grazing in dry and spiny forests; however, today many herders have adopted m*iarakandrovy*, a strategy in which livestock are herded during the day and brought to the village at night (Ratsirarson 2003). As a result, the mobility of livestock has been reduced, and environmental impacts have begun to be concentrated.

Under the m*iarakandrovy* grazing strategy, herders typically utilize abandoned agricultural land; therefore, forests in southern Madagascar are seldom converted to pasture (Kaufmann and Tsirahamba 2006). According to Casse et al. (2004), an increase in agricultural production will typically signify an increase in cattle breeding. This may occur as a result of increased grazing lands opened up by agricultural activities or be due to increased investment in cattle stock with income from agricultural production.

Even if livestock are not largely responsible for forest loss in southern Madagascar, there is a long-standing belief that livestock grazing is generally bad for forests (Dambach 1944, Brower and Dennis 1998). Evidence suggests that livestock grazing (among other activities) is negatively impacting forests around Beza Mahafaly

Special Reserve (BMSR) with significantly reduced ground cover and increased grass species found outside of the protected area (Sussman and Rakotozafy 1994, Sauther and Cuozzo 2009); consequently, there is concern that livestock negatively impact populations of forest species, especially lemurs. Nearly 20 years ago, Richard and Dewar (1991) argued that "while the presence of bovids may have little immediate bearing on lemur ecology, their introduction undoubtedly had a major impact on the vegetation on which lemurs depend for their survival, an impact continued and possibly magnified today" (Richard and Dewar 1991). Yet, today, lemur-livestock interactions remain poorly studied.

Much of the research on the pastoralism-wildlife controversy in semi-arid regions is focused specifically on rangelands (Homewood and Rodgers 1984, du Toit et al. 2010), which is not altogether relevant to the livestock-lemur controversy playing out in southern Madagascar. The primate-livestock issue in the dry forests of southern Madagascar is fairly unique; consequently, research from other systems is not likely to provide much insight for researchers working in this region. Heretofore, information on livestock-lemur interactions has been anecdotal (Richard and Dewar 1991, Sussman and Rakotozafy 1994, Gould et al. 1999), but data on the feeding ecology of lemurs and livestock suggests there may be both direct and indirect interactions.

During the dry season, there are less food resources for both lemurs (Sauther 1998, Sauther et al. 1999, Gould 2006, Sauther and Cuozzo 2009) and livestock (Pers. Comml, Efitiria). *Lemur catta* (catta) and *Propithecus verreauxi* (sifaka) both forage for food along the ground especially during the long dry season; fully 50% of the food resources exploited by catta are located near or at ground level (Sauther 1998). In

particular, catta relies heavily on two ground-level leaf resources, *Ipomoea batatas* and *Argemone mexicana* (Sauther and Cuozzo 2009) late in the dry season. Lemurs and livestock are, therefore, in direct competition for some food resources.

Herders also rely more heavily on forest browse to feed livestock during the dry season. In gallery forest, large tree limbs from *Tamarindus indica*, a fallback food for catta (Sauther and Cuozzo 2009), are frequently cut as fodder for livestock. In dry deciduous forest, patches of small-stemmed trees are felled for livestock browse. Lopping and felling may alter the microclimate of the forest resulting in the absence (or presence, in areas opened by clearing) of plant species not typically found in either forest class. In particular, as noted in Chapter 3, high sifaka density in both protected dry deciduous forest class and unprotected gallery forest class suggests there may be similarities in these forest classes to which sifaka respond.

This is a preliminary investigation into livestock-lemur-forest interactions in the forests in and around Beza Mahafaly Special Reserve. Comparisons were made between grazed and ungrazed forest sites (Regions 1, 2, 4, and 5 from Chapter 3) to explore differences in forest condition and lemur density. In Chapter 3, comparisons were made of lemur density by forest class with respect to status (irrespective of the spatial arrangement of the forest). Here comparisons were made within mixed-forest regions (Chapter 3) that were either predominantly-gallery forest ("gallery") or predominantly-dry deciduous ("dry") in order to examine differences in density between specific areas in the study area.

I hypothesized that grazed forest regions would exhibit significantly higher levels of disturbance—as evidenced by parameters such as higher percent canopy openness,

lower tree basal area, and uncharacteristic tree species composition—than ungrazed regions. I also hypothesized that 1) dry season catta density would be significantly higher in the ungrazed "gallery" region than in the grazed; and 2) dry season sifaka density would be significantly higher in ungrazed "dry" region than in the grazed.

#### Methods

#### Study area

Three paired regions in the study area described in Chapters 1 and 2 had similar forest composition (Regions 1-6) and shared the same longitudinal position between the road to Mahazoarivo and the Sakamena River (Figure 4.1). Each pair was comprised of one predominantly-gallery ("gallery") forest site (Regions 1-3) and one predominantly-dry ("dry") deciduous site (Regions 4-6). Two pairs were unprotected (Regions 1 and 4 and Regions 3 and 6) and one pair protected (Regions 2 and 5).

Regions 2 and 5 had been closed to grazing for the past 30 years. Human activities in the two unprotected pairs were dramatically different. Activities in Regions 1 and 4 were attributed primarily to livestock grazing, while human activities in Regions 3 and 6 included grazing, as well as, fuelwood collection; soil compaction by oxcarts, vehicles, tents, and frequent foot traffic; livestock grazing; forest clearing for construction of camp buildings; and trash disposal (in pits and on the forest floor). The Beza Mahafaly Special Reserve (BMSR) camp site is located within Region 3, and an oxcart trail running through the area, as well as to the road to points beyond.

Forest descriptions by others working in Regions 3 and 6 correspond with those from this study (Gemmill and Gould 2008, Sauther and Cuozzo 2009). In order to highlight differences in forest structure between grazed forest regions and adjacent

ungrazed ones, comparisons were made between the 133 ha grazed area comprised of Regions 1 and 4 and the 89 ha ungrazed area comprised of Regions 2 and 5 (Figure 4.2).

Forest structure measurements were estimated using 80 point transects within the ungrazed area (Regions 2 and 5) and 77 point transects in the grazed (Regions 1 and 4) as described in Chapter 3 (Figure 4.1). The species of all plants within 10 m of each point with a height of 1 m or more were identified with the assistance of a Malagasy expert. Plant species richness was calculated for each 10 m sample plot. Tree basal area was also estimated with a 10-factor cruising prism using the Bitterlich method (Grosenbaugh 1958).

Canopy openness was calculated indirectly using digital hemispherical photographs. All photos were taken with a Nikon Coolpix 990 digital camera with an attached Nikon FC-E8 fisheye lens mounted on a tripod with the lens positioned 1 meter off the ground. Using the software Gap Light Analyzer (GLA), percent canopy openness was calculated from the digital photos.

Forest structure characteristics were compared using a student's unpaired t-test to determine if there were significant differences in the means of structural parameters between the grazed and ungrazed areas. All tests were two-tailed with significance set at p = 0.05.

Lemur density was estimated in the mixed-forest regions in order to make comparisons in the study area (as described in Chapter 3). Comparisons were made by both status and forest class to account for differences observed in lemur density by forest class in Chapter 3. Paired-tests for differences in density by region were performed using a z-test approximation of Satthewaithe's Approximation (Thomas et al. 2006).

## Results

The ungrazed area (Regions 2 and 5) was comprised of 55% gallery forest, 43% dry deciduous, and 2% not forest, whereas the grazed (Regions 1 and 4) was comprised of 65% gallery, 28% dry deciduous, 6% not forest, and <1% spiny. The spatial arrangement of forest classes differed between the two areas; there was a large patch of dry deciduous forest situated in the middle of the gallery forest in the grazed area; while patches of dry forest in ungrazed gallery forest were found along forest transition areas or forest edges.

The imposed region boundaries designed to separate forest regions along transition areas (Chapter 3) resulted in areas having similar forest composition; the two eastern regions (Regions 1 and 2) were each characterized by over 80% gallery forest, and the two western regions (4 and 5) were each characterized by nearly 90% dry deciduous forest (Table 4.1). The major difference between regions was found in the balance of forest in the western regions; the balance of the ungrazed site was gallery forest, while in the grazed area it was split between spiny and gallery forest. Spiny forest represented 2% of Region 4, while there was none in Region 5—its ecological analogue.

Total plant richness across the 220 ha study area was 35 species, with 34 in the grazed area plots and 27 in the ungrazed. The only plant species present in the ungrazed plots but absent from the grazed was *Metaporana parvifolia* (Convolvulaceae), an understory species eaten by both lemur species (Yamashita 2002). Of the eight plant species found in the grazed plots, but altogether absent from the ungrazed plots, *Albizia polyphylla* (Mimosoideae) (found elsewhere in the BMSR region in dry deciduous forests) was present in the grazet number of grazed plots (n=13).

Total plant species richness (s) was the same (s=25) in the two "gallery" regions (Regions 1 and 2), though they did not share the same species composition. Notable absences from the grazed "gallery" plots included *Terminalia seyrigii* (Combretaceae), a tree utilized by both catta and sifaka and also used as livestock fodder; and *M. parvifolia*, an understory species favored by catta. A notable presence in the grazed "gallery" site that was absent from the ungrazed site was *Albizia polyphylla* (Mimosoideae), a large tree often found in sunny areas at forest edges. In addition, there were some species present in grazed "gallery" plots that were typical of drier microclimates (e.g., *Commiphora brevicalyx*, *Alluaudia procera*, *Rhigozum madagascariensis*).

Total plant species richness was higher in the grazed "dry" site (Region 4) (s=27) than in the ungrazed (Region 5) (s=22), and the two areas shared 20 species in common. Species present in the "dry" grazed site, but absent in the ungrazed site—*Commiphora brevicalyx* (Burseraceae), *Xerosicyos danguyi* (Curcurbitaceae), *Euphorbia stenoclada* (Euphorbiaceae), *Alluaudia procera* (Didiereaceae), *Opuntia* sp. (Cactaceae), *Aloe divaricata*, (Liliaceae)—were more typical of spiny forest, and these species were found largely at sampling points classified as spiny forest in Region 4.

Mean plant species richness per plot was not significantly different between the two "gallery" regions (grazed and ungrazed), but mean plant species richness per plot was significantly higher in the grazed "dry" region than in the ungrazed "dry" (Table 4.2). Mean plant species richness per plot was significantly higher in ungrazed "dry" than in ungrazed "gallery"; however, there was no significant difference in mean plant species per plot between grazed "gallery" and ungrazed "dry" (Table 4.3).

Tree basal area in the ungrazed "gallery" forest region was not significantly different from that of grazed "gallery"; yet tree basal area in the ungrazed "dry" forest region was significantly higher than in the grazed "dry" (Table 4.2, Figure 4.3). There was no significant difference in tree basal area between ungrazed "gallery" and ungrazed "dry" or between ungrazed "dry" and grazed "gallery" (Table 4.3).

Percent canopy opening was neither significantly different between the two "gallery" regions, nor the two "dry" regions (grazed and ungrazed) (Table 4.2, Figure 4.4); however, the ungrazed "dry" region was significantly more open than either the grazed or the ungrazed "gallery" region (Table 4.3, Figure 4.5).

Neither sifaka nor catta average group size was significantly different between grazed and ungrazed areas (Table 4.2). The majority of catta groups were located within gallery forest, particularly in the interior of the forest (Figure 4.6). Most sifaka groups, on the other hand, were located either in dry deciduous forest or at transition areas between dry deciduous and gallery (Figure 4.7).

There was no significant difference in catta density between grazed and ungrazed "gallery" forest regions, or between grazed and ungrazed "dry" forest regions (Table 4.4, Figure 4.6). Moreover, there was also no significant difference in sifaka density between grazed and ungrazed gallery forest regions. Sifaka density was significantly higher in the ungrazed "dry" region than in that of the grazed (Table 4.4, Figure 4.7); however, sifaka density in ungrazed "dry" was not significantly different from that in grazed "gallery".

Plant species richness was highest in the ungrazed "dry" region corresponding to the area of highest sifaka density. Plant species richness was not significantly different between the two gallery forests (grazed and ungrazed), and neither was sifaka density

between ungrazed "dry" and either of the "gallery" forests; yet, sifaka density was higher in the grazed "gallery" than in ungrazed "gallery".

#### Discussion

#### Forest structure

Grazing impacts on forest structural parameters appear to be more pronounced in the "dry" forest region than in the "gallery", as reflected in tree basal area and especially, species composition. This is likely due to differences in how herders use the forest classes. For instance, herders frequently lop branches off *T. indica* trees in the gallery forest, but entire trees are seldom cut. However, in the "dry" forest, an area of smallstemmed trees may be cleared creating a small opening in the forest.

Other researchers found significant differences in forest parameters between unprotected and protected gallery and dry deciduous forests around Beza Mahafaly Special Reserve (Sussman and Rakotozafy 1994, Gemmill and Gould 2008, Sauther and Cuozzo 2009); however, it is important to note that these researchers compared the ungrazed Parcel I to adjacent forests to the south, which are impacted by a host of degrading activities. The northern forest site was specifically selected for this study because grazing represents the principal degrading activity in the site.

Based on the results of this study, it may be difficult to differentiate between grazed (or more generally, disturbed) and ungrazed forests using spectral data from remote sensors. This is not surprising given that sensors rely largely on information from the canopy and percent canopy cover did not differ significantly between grazed and ungrazed sites.

Differences in the spatial arrangement of transition zones in the two areas, grazed and ungrazed, may be due either to natural transition zones or to disturbance events. It seems likely that in this study area, both forces are at work. Given the presence of eastwest moisture gradient in the study area, it is no surprise that there is a dry forest gradient ranging from gallery, the wettest, to spiny forest, the driest (Sussman and Rakotozafy 1994). Clearly there will be areas of natural transition between forest classes along this gradient. However, disturbance is a confounding factor, as disturbance activities that negatively impact plant regeneration and overstory may create disturbed areas that mimic natural transition zones.

Dry deciduous forest patches along the southern edge of the ungrazed area are likely due to edge effects from the road running alongside the southern boundary of the Parcel I. It seems that gallery forest exposed to excess light over time will transition to dry deciduous forest. This theory is supported by data collected from the large patch of dry deciduous forest located in the center of the gallery forest in the grazed area, assuming, of course, that this patch was a fully intact patch gallery forest prior to the introduction of livestock activities. There was evidence of significant disturbance here in the form of lopping, felling, and livestock corrals.

On the ground, grazing impacts may be more localized to the understory, and in cases of excessive lopping, to canopy cover. To highlight differences between grazed and ungrazed areas, researchers may want to focus future efforts on the collection of forest microclimate variables (e.g., soil moisture, differences in soil and air temperature, etc.) and ground-level vegetation, especially seedling regeneration. While the overstory of a grazed forest may resemble that of an ungrazed one—despite years of grazing

activity—differences are likely to be realized if regeneration in grazed forests fails to keep pace with regeneration in ungrazed forests.

While forest structural variables largely failed to distinguish between grazed and ungrazed forest in this study, results highlight the potential for forest structural measures to help refine land cover classification of forest classes. In particular, percent canopy opening may be particularly useful in distinguishing between gallery and dry deciduous forest. Random forest classifiers can incorporate ground-level data, in addition to spectral data, so the inclusion of forest structural measures should be considered in future mapping efforts using a random forest classifier.

## *Lemur density*

Catta density in ungrazed "gallery" was the highest in the study region, yet it was not significantly higher than in the ungrazed "gallery" suggesting that despite disturbance, the grazed area was functionally similar to the ungrazed "gallery" forest. This may be due to the dominance of *T. indica* in both regions and the similarity in forest structural properties of the two regions. On the other hand, catta density was not high in either dry deciduous forest region. Forest structural parameters in the grazed dry deciduous stratum certainly did not favor presence of catta, but density was already so low in the ungrazed stratum, that there was no significant difference in catta density between dry deciduous sites. These results suggest that areas experiencing grazing activities that do not significantly alter forest structure may support densities of catta similar to those in ungrazed areas.

Since most of the forests throughout the southwest are undergoing grazing activities, densities of catta observed in grazed regions may be more representative of the

actual densities of the majority of populations than are other published estimates; contrastingly, catta density may be artificially high in those ungrazed areas that exclude livestock grazing.

Unlike catta, the diet of sifaka is eclectic (Simmen et al. 2003) and fairly balanced (Howarth et al. 1986, Yamashita 2002). Simmen et al. (2003) found that sifaka at Berenty Special Reserve ate a greater diversity of plant species and food items than did catta. And indeed, plant species richness was higher in this study's ungrazed "dry" forest region than in the ungrazed "gallery". It was, therefore, not surprising to find that sifaka density was high in the ungrazed "dry" region. However, sifaka density was significantly lower in grazed "dry" forest than in either of the "gallery" forests. Given their affinity for a varied diet, decreased sifaka density in grazed "dry" forest may be related to lower plant species richness and smaller tree basal area.

On the other hand, sifaka density was higher (although not significantly) in grazed "gallery" than in ungrazed suggesting that sifaka may be responding favorably to changes in the landscape here. Since there was no significant difference in any of the measured forest structure variables between grazed and ungrazed "gallery", it's unclear what, if any, variable may explain higher sifaka density in grazed "gallery". However, given their propensity to eat on the forest floor during the dry season, sifaka could be responding to understory species less than 1 m present in the grazed site but not present in the ungrazed.

Disturbance may actually increase plant diversity in gallery forests by introducing light gaps into otherwise closed forest environments and promoting seed propagation (Gemmill and Gould 2008). The grazed "gallery" region included plants more typical of dry deciduous habitats such as *A. polyphylla*, a species eaten by sifaka (Yamashita 2002).

It appears that sifaka populations may actually benefit from grazing in gallery forests, so long as there remains an area of largely-unfragmented gallery forest having a nearly intact forest structure. Thus, I speculate that sifaka density in and around BMSR is correlated more with forest structure or plant species diversity than with specific plant species or an environmental gradient.

On the other hand, sifaka may be especially sensitive to grazing in dry deciduous forests, where both plant species richness and tree basal area were shown to be lower. Livestock grazing activities can impact forest indirectly through soil compaction, reduced seed germination, and promotion of a shrub-dominated understory (Sussman and Rakotozafy 1994, Gillespie et al. 2000), or directly through both tree chopping and treebranch lopping.

Furthermore, gaps or edges may contain high-quality food resources for lemurs (Ganzhorn 1995, Lehman 2006), and presence of numerous edges between gallery and deciduous dry forests may also explain high sifaka densities in protected dry deciduous and disturbed gallery forests. The spatial arrangement of sifaka groups supports this hypothesis.

### Pastoralists as conservationists?

Environmental variability is inherent in the arid and semi-arid habitats of the south. Agriculture here is high-risk due to drought, locusts, and cattle diseases (Kaufmann 2004) and food crop yields in the south are low (maize, cassava, sweet potatoes, and some rice) accounting for only about a quarter of income (Hewitt 1992). Pastoralism, on the other hand, provides revenue that allows people to live in this harsh environment (Kaufmann 2004). Both the Mahafaly and the Antandroy have evolved
strategies for dealing with their unpredictable environment. Local residents take advantage of variability by gathering forest foods such as honey, digging up fleshy roots, moving cattle between green pastures and recently harvested croplands (Olson 1988), and reserving forest groves for livestock-use at critical times (Tengö et al. 2007). Maintaining variability in natural resource use is an important feature of these groups' culture (Olson 1988).

Buffer resources are provided by common areas considered to be "lands of last resort". These areas are open to all and comprise habitats of varying classes including forest, dry bush, marsh, and riverine forest. During hard times, local communities rely on resources such as building materials, fruits, greens, and livestock browse that can be procured from these seemingly neglected lands. What may appear to be unused or underutilized spaces, are instead areas of actual critical importance (Olson 1988).

Livestock also play a role in some measure of protection of the forest (Morat 1973). While herders favor use of pastures for their cattle, they also propagate fodder trees and maintain forests for reserves in case pastures give out. Many communities also set aside patches of forest as "forested grazing reserves" for fodder and browse in order to maintain their most important investment—their forests (Kaufmann 2004). As a community, herders respect the forest reserves, for they are their last line of defense against loss of their capital.

Forest cover is critically important to herders in southern Madagascar as it provides forage during the long dry season and it also provides protection to herds from cattle thieves (Casse et al. 2004, Kaufmann and Tsirahamba 2006). Browse, the shoots and leaves of trees and shrubs, are an important component of the dry season livestock

diet, as at this time, pasture productivity declines and the nutritional quality of grasses deteriorates (Atta-Krah 1989). Forest cover also provides much-needed shade for animals and herders (Le Houerou 1987) and slows the desiccation of herbaceous growth in the understory (Reid and Ellis 1995). These attributes benefit livestock and wildlife alike.

In other areas of the south, communities have established "taboo forests", areas in which human-use is prohibited. Researchers mapped a network of "taboo forests" near Ambovombe and noted that the small forest fragments there impart benefits to area wildlife (Tengö 2004). Furthermore, trees in these small forests may serve as sources of seed from which forest expansion may potentially occur (Bodin et al. 2006). Some of the forest patches have been standing for at least the last 50 years (Tengö 2004) attesting to the effectiveness of local forest protection measures, at least on a small scale. In other areas, communities set aside "sacred forests" to be used only for burial and ceremonial purposes.

### Conclusion

Lemurs have been living with livestock for generations. Livestock are not newcomers to this system and there is some reason to believe that they can co-exist. While livestock could be responsible for degrading activities in forest lands, in many cases they may not be the primary contributors to forest loss. In addition, their presence in the forest may not always be as damaging as conventional wisdom would have us believe. Furthermore, their presence, in some areas, could even serve to maintain species diversity in small isolated forest patches.

While conditions in gallery forest may typically limit deposition and establishment of outside species due to dense canopy cover (Seidler and Plotkin 2006),

livestock grazing may introduce plant species not naturally found in gallery forest by dispersing seeds on their fur and/or in their feces and also by creating understory gaps that increase chances for seed germination. On the other hand, seedling density may also be reduced in grazed areas due to trampling. Still, livestock impacts that do not denude the landscape may promote successional processes (Christensen 1989); furthermore, livestock could be dispersing seed between isolated forest fragments (Couvreur et al. 2004) which, if true, could actually promote ecological restoration. In other words, under certain circumstances, cattle may actually play a role in "catalyzing successional processes" (Miceli-Méndez et al. 2008).

Region	Area	Gallery	Dry	Spiny	Points
	(ha)	(%)	(%)	(%)	(no.)
1 (Grazed) 2 (Ungrazed) 4 (Grazed)	95 57 33	89 81 5	8 18 92	0 0 2	56 53 21
5 (Ungrazed)	31	13	87	0	28

Table 4.1 Forest class make-up of study regions.

	Ungrazed	Grazed	t	p value
Variable	Mea	n	value	2-tailed
Plot species richness, "gallery"				
(Region 2 vs. 1)	5.58	6.27	-1.56	0.12
Plot species richness, "dry"				
(Region 5 vs. 4)	6.75	10.81	-5.67	< 0.001
Tree basal area, "gallery"				
(Strata 2 vs. 1)	10.63	9.58	1.55	0.12
Tree basal area, "dry"				
(Strata 5 vs. 4)	9.64	6.38	3.86	0.000
% canopy opening, "gallery"				
(Strata 2 vs. 1)	19.42	18.3	0.58	0.56
% canopy opening, "dry"				
(Strata 5 vs. 4)	25.86	29.7	-1.33	0.19

Table 4.2 Student's unpaired t-tests for significant differences in the means of forest structural parameters and lemur group size between the grazed and ungrazed sites.

	"Gallery"	"Dry"	t	p value
Variable	Mea	ın	value	2-tailed
Plot species richness, ungrazed "dry" vs.	5 59	675	2.01	0.05
ungrazed "gallery" (Region 5 vs. 2)	5.58	6.75	-2.01	0.05
Plot species richness, ungrazed "dry" vs.				
grazed "gallery" (Region 5 vs. 1)	6.27	6.75	-0.89	0.38
Tree basal area, ungrazed				
(Region 2 vs. 5)	10.63	9.64	1.15	0.26
Tree basal area, grazed "gallery" vs.				
ungrazed "dry"				
(Region 1 vs. 5)	9.64	9.58	0.07	0.94
Percent canopy opening, ungrazed				
(Region 2 vs. 5)	19.42	25.86	-3.74	< 0.001
Percent canony opening grazed "gallery"			0171	101001
vs ungrazed "dry (Region 1 vs. 5)	18 3	25.86	-3 57	<0.001
vs. ungruzed ury (region 1 vs. 5)	10.5	25.00	5.57	<0.001
Sifaka group size	5.19	5.08	0.19	0.85
Catta group size	8 90	931	-0.39	0.70
Cullu group size	0.70	7.51	0.57	0.70

Table 4.3 Student's unpaired t-tests for significant differences in the means of forest structural parameters and lemur group size between the gallery and dry sites.

Region	Area	Gallery	Dry	Spiny	Samples	Total	Groups	Avg GroupProbabilityDensity (catta/sq. k			km)		
								Size	of		CV		
	(ha)	(%)	(%)	(%)	(no.)	Effort	(no.)	(%CV)	Detection	Estimate	(%)	df	95 % CI
1	95	89	8	0	60	120	17	9.0 (10.0)	0.36	2.7	30	56	1.5 4.9
2	57	81	18	0	53	106	18	9.7 (7.6)	0.36	3.6	28	58	2.0 6.2
4	33	5	92	2	21	42	1	7.0 (0.0)	0.36	0.2	100	16	0.0 0.5
5	31	13	87	0	27	54	6	8.5 (8.5)	0.36	0.8	46	18	0.3 1.9

Table 4.4. Distance analysis results by region for *L. catta.*. The number of groups is after truncation. Density is individuals per sq. km.

Table 4.5. Distance analysis results by region for *P. verreauxi*. The number of groups is after truncation. Density is individuals per sq. km.

Region	Area	Gallery	Dry	Spiny	Samples	Total	Groups	Avg Group	p Probability Density (sifaka/so		ka/sq.	km)	
								Size	of		CV		
	(ha)	(%)	(%)	(%)	(no.)	Effort	(no.)	(%CV)	Detection	Estimate	(%)	df	95 % CI
1	95	89	8	0	60	120	30	4.8 (8.1)	0.34	2.6	23	78	1.6 4.0
2	57	81	18	0	53	106	8	4.8 (10.8)	0.34	2.1	27	52	1.2 3.5
4	33	5	92	2	21	42	2	6.0 (0.0)	0.34	0.7	71	82	0.2 2.4
5	31	13	87	0	27	54	15	5.5 (8.7)	0.34	3.3	30	37	1.8 5.9

Comparison	Density (le	emurs/ha)	Standar	d Error	Z statistic	D	
I I I I I	Ungrazed	Grazed	Ungrazed	Grazed	_	1	
Catta, "gallery" Strata 2 vs 1	3.57	2.75	1.01	0.81	0.63	0.53	
Catta, "dry" Strata 5 vs 4	0.77	0.17	0.35	0.17	1.54	0.12	
Sifaka, "gallery" Strata 2 vs 1	2.08	2.56	0.56	0.60	-0.59	0.55	
Sifaka, "dry" Strata 5 vs 4	3.26	0.68	0.97	0.49	2.36	0.02	
Sifaka, "dry" ungrazed vs. "gallery" grazed Region 5 vs 1	3.26	2.56	0.97	0.60	0.61	0.54	
Sifaka, "dry" ungrazed vs. "gallery" ungrazed Region 5 vs 2	3.26	2.07	0.97	0.56	1.05	0.29	
Sifaka, "dry" grazed vs. "gallery" grazed Region 4 vs 1	0.68	2.56	0.49	0.60	-2.44	0.15	

Table 4.6 Comparison of *L. catta* and *P. v. verreauxi* density by sampling regions illustrated in Figure 4.1. Paired-tests for differences in density by strata were performed using a z-test approximation of Satthewaithe's Approximation.



Figure 4.1 Study regions and sampling points as located within the larger study area



Figure 4.2 Forest classification of the two study sites (4 regions)



Figure 4.3 Tree basal area by forest region for the grazed and ungrazed sites



Figure 4.4 Percent canopy cover by forest region for the grazed and ungrazed sites



Figure 4.5 Percent canopy opening



Figure 4.6 Catta groups in ungrazed (bold) and ungrazed sites



Figure 4.7 Sifaka groups in ungrazed (bold) and ungrazed sites

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#### **CHAPTER 5 - DISCUSSION**

# Introduction

Initially, I was motivated to begin this research by an interest in the spatial patterns of lemurs within different classes of dry forest; however, the absence of data on lemur populations outside of protected areas prompted me to expand my study into unprotected lands. My first challenge was to locate a suitable map of my study area. On the ground, it was clear that there were differences in forest classes—both structurally and ecologically—but available maps failed to capture the heterogeneity in the landscape. Therefore, I set out to map the land cover of the region. It was clear early on, that methods that have been used to classify tropical wet forests were likely not going to be effective at discerning differences between forest classes in my study area. Therefore, I used the Random Forest classification method which is especially suited for distinguishing between complex vegetation.

My forest classification is a useful tool for describing lemur habitat, as its forest classes reflect differences in plant species composition to which lemur species appear to respond. In this case, the classification paired with on the ground lemur surveys enabled me to identify lemur habitat that had not previously been described. This expanded definition of lemur habitat will prove useful in the management of unprotected areas in this and similar regions. In addition, the map classification is not necessarily restricted to lemur studies, as it should prove useful for modeling the distribution of other forest species as well (e.g., Madagascar radiated tortoise, *Geochelone radiata*).

One limitation of this map classification—and others—is the absence of information about extent of disturbance within forests. Clearly there is a difference in levels of disturbance experienced by forests in the study area, but given that there is natural moisture gradient present in the site, characterizing disturbance is made more challenging since typical disturbance activities here also impact moisture availability. Some environmental variables related to micrcolimate such as soil moisture, soil hardness, and seedling regeneration may serve as particularly good surrogates for disturbance. Remote sensors would provide an efficient means to capture this information synchronously from multiple sites throughout multiple seasons. Based on results from this study, additional data on microclimate may help to differentiate levels of disturbance within forest classes.

We've seen in this study that spectral differences in forest canopy can separate forest classes within this study area, especially using images from the dry season. By combining spectral data with disturbance information such as microclimate data and forest structure measurements, we may be able to begin describing a spectrum of disturbance, using ungrazed lands as a reference condition for minimal disturbance. After locating environmental variables that characterize disturbance regimes, we'd ideally find a corresponding measure in satellite imagery to allow researchers to identify, and even characterize the extent of, disturbance using remotely sensed imagery. Clearly it would be more efficient to detect differences in disturbance levels from the air. In other words, the ability to characterize disturbed forests using remotely sensed imagery, would be ideal. By relating the nature of disturbance to the environmental conditions associated with that disturbance and then correlating this information with lemur density, we can compile a more complete picture of the status of both lemur species based on forest condition (not just forest class). Given that the vast majority of forests in southern Madagascar are not protected, this type of analysis may be the best method of assessing population status across the region.

A further area of interest of mine related to the study of disturbed forests is the characterization of "ecologically intact" forests. Obviously, the first challenge here is to define ecologically intact through some measure of ecological function. Lemur density, itself, is just one measure of ecological function, and it may be appropriate if *L. catta* and/or *P. verreauxi* are umbrella species, that is a species whose very protection will indirectly protect many other species in the community; however, other measures may be better gauge of overall function.

Acoustic monitoring is one such method that may provide a suitable measure of overall forest function as it captures a wide range of sound data from multiple species including birds, insects, and lemurs. Indeed, acoustic monitoring may be an efficient replacement for field rapid biodiversity assessments. At the least, autonomous acoustic recorders can provide a first level assessment of potential biodiversity from which potential field sites could be selected for more intensive surveys.

#### **Conservation Implications**

In this study area, lemur density for both species was highest in forests near the river. Persons interested in locating viable populations of either species may want to focus on locating riverside forests, either gallery or dry deciduous; yet, it is their

proximity to water that places these forests at the most risk for degradation from agriculturalists and pastoralists. Preserving and protecting these forests may entail helping communities either to manage them (e.g., sacred forests, communal forests, etc.) or to place remaining riverine remnants in national, community, or private forest reserves.

*Lemur catta* and *Propithecus verreauxi* share the same forests, but they appear to have slightly different conservation needs. Within this landscape, catta appear to prefer gallery forest, regardless of its degree of disturbance. It may be less important to provide grazing-free gallery forests than to maintain the structural integrity of remaining gallery forests on the landscape. However, if gallery forests are acting as ecological sources, the loss of gallery forest could be catastrophic to catta populations and result in local extinction of the species. Without survival and fecundity data from groups living exclusively in dry deciduous habitats, we do not yet know if they are either viable or sink populations. In the absence of information, the prudent position would be to increase the protection of gallery forests, especially those with tamarind trees.

Since sifaka groups are spread more evenly across the landscape, the loss of particular macrohabitats at a local scale may not be as critical as it may be for catta. However, given sifaka's predilection for a diet of diverse plant species, it is important to protect some dry deciduous forests from grazing; barring that, gallery forests undergoing grazing, but without incurring radical changes in forest structure, may serve as an adequate substitute.