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Flowering Phenology:

Lemurs, People, & Climate Change

A Thesis in Environmental Studies and Sustainability

by

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Abstract

In this thesis, I explore the ways in which the changes observed in flowering phenology in Talatakely, Ranomafana National Park (RNP), Madagascar, are intertwined with the lemurs, the people of Madagascar, and climate change. The data were collected from an ongoing monitoring of fruiting trees found in the secondary growth forest that *Propithecus edwardsi* feed on. The precipitation data were collected by the Tropical Ecology Assessment and Monitoring (TEAM) program. Previous studies have associated high levels of productivity in the rainforest to high levels of rainfall. I hypothesized that due to climate change we would no longer be able to associate high levels of rainfall to high levels of flowering based on the flowering phenology and rainfall data gathered from 2012 to 2018. Through statistical analyses using the Software RStudio, I found that there was no relationship between the high levels of flowering, when compared to the monthly sum of rainfall over seven years, $r(N = 28{,}024) = -0.0086$, $p = 0.26$. In addition, ancillary analyses confirmed that Madagascar, specifically RNP, is experiencing longer dry seasons. Variability in rainfall will put a stain on food supply for both lemurs and people which will aggravate the tension between a need to save the biodiversity while still respecting local populations. Future work would look at other abiotic factors that influence the flowering processes, such as iridescence and soil composition.

Key words: *flowering, phenology, lemurs, precipitation, climate change, Madagascar*

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They say it takes a village, and this is the village that made this possible.

To all, I am forever grateful.

Although this is the final copy of this thesis, it should be treated as a draft. This piece of writing is a work in progress, a project in progress just like wildlife conservation.

Table of Contents

Background

1.1 Objectives

This research is a continuation of a recent study that looked at the fruiting phenology. The study concluded that fruiting patterns recently have been more variable than in the previous years due to climate change but they could still associate high levels of fruiting to high levels of rainfall (Dunham et al. 2018). The objective of this thesis is to understand the current relationships between the cyclical and seasonal timing of biological events in the flora and contextualize how this change influences lemurs and people. My research examines the flowering patterns in the secondary rainforest of Talakely in Ranomafana National Park, Madagascar and compares them to the monthly sum of rainfall. Flowers serve two purposes. The first is *P. edwardsi* consume flowers to supplement their diet. The second is that they are the reproductive system of plants and an indicator of the upcoming fruit season. An analysis of the impact of the ever changing phenology of flowers provides insight on the impact of food availability for both lemurs (*P. edwardsi)*. I hypothesized that due to climate change we would no longer be able to associate high levels of rainfall to high levels of flowering based on the flowering phenology and rainfall data gathered from 2012 to 2018.

Madagascar is an island roughly the size of Texas off the eastern coast of Africa, that hosts an abundance of unique flora and fauna (Tyson, 2013). Madagascar's biological diversity was introduced to the world through Sir David Attenborough in the early 1960s. In a four episode documentary series, *Madagascar*, he narrates, "nature seems to have retreated there [in Madagascar] into a private sanctuary, where she could work on different models, from any she has used elsewhere" (Attenborough et al., 2011). The country has a total of 13,000 plant species of which 89% are endemic (the state of existing nowhere else), 155 mammal species of which 92% are endemic, 381 reptile species of which 96% are endemic, and 228 amphibian species of which 99% are endemic (Ganzhorn et al., 2014).

On May 27th, 2019, I embarked on a six week field school to Madagascar with 12 of my peers under Stony Brook University where we were exposed to an abundance of biodiversity and culture. In our 24-passenger bus, we left the capital city Antananarivo (18.87° S, 47.51° E) for Ranomafana (21.25° S, 47.45° E) in the South using the RN 25 (one of the main highways) (**Fig. 1**). We drove through hills that were once completely covered with trees but were now dotted with lonesome bushes here and there and terraces used for farming. We passed brick houses with bright blue wooden windows. On the side of the road, people oftentimes carrying wood or selling goods would wish us well and wave as we yelled the formal greeting out the window, *salama*, meaning hello. We would observe them fall back giggling, as they yelled "*vazahaa",* meaning foreigners.

Figure 1. Screenshot of political and geographical map taken from Google maps map of Madagascar.

Upon our arrival on the island, we were immediately exposed to the diversity of some mammals but mostly reptiles in Peyrieras Reptile Reserve (18°55'52.7"S, 47°56'59.9"E) 10 km east of Antananarivo, the capital city. We saw a collection of reptiles from the famous Leaf-tail geckos (*Zonosaurus boettgeri*) to Parson's chameleon (*Calumma parsonii*) (**Fig. 2**). The first lemur we saw, Verreaux's sifaka (*Propithecus verreauxi*), was also in the reptile sanctuary (**Fig. 3**). As we continued to explore the various ecosystems of the country we encountered different lemurs. We experienced different weather from the humidity of the rainforest early in the day to the dryness of the spiny desert at the end of the day.

Figure 2. Left image is that of *Zonosaurus boettgeri* (Leaf-tail gecko) and the image on the right is my hand holding *Calumma parsonii* (Parson's chameleon). (Images taken by Maïmouna Kanté)

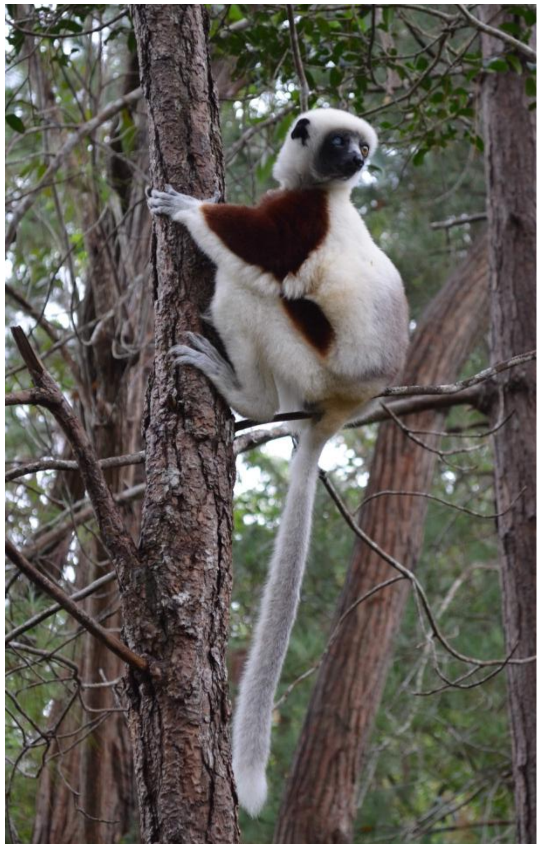

Figure 3. Verreaux's sifaka (*Propithecus verreauxi*) at Peyrieras Reptile Reserve. (Image taken by Julie Micko)

The diversity in culture was evident through our meals and our interactions with various peoples. Madagascar has more than 20 ethnic groups that co-exist and whose cultural heritage stem from Southeast Asia, India, Africa and the Middle East (Tyson, 2013). Through studies done in linguistics, genetics, and plant analyses, archeologists have been able to track the arrival of the present-day Malagasy people back to approximately 2,000 years ago (Crowther et al., 2016). For those of African descent, analyzing linguistics and genetics proved to be very fruitful and when analyzing the Asian ancestry, they found great similarities between some Asian plants and other early farming methods in Madagascar (Crowther et al., 2016). As for us, we had meals that consisted mainly of rice, zebu, raw sugar cane, coffee infused with sugar cane, and boiled cassava. To further understand one of the many ethnic groups, we were given the opportunity to immerse ourselves in a Tamale (ethnic group) village. We met the king of the village and asked questions about what his hopes were for the future. He told us that he had hopes of providing food and education for the children. At that moment, my peers and I were once again reminded of the poverty and food security issues the country faces.

The emphasis on poverty when reading about Madagascar is overwhelming. According to the World Bank, their Gross Domestic Product (GDP) was USD 13.853 billion in 2018 compared to the United states with a GDP of USD 20.544 trillion (*Madagascar | Data*, n.d.; *United States | Data*, n.d.). As the country attempts to fill in the gaps of poverty it is also facing an exponential growth in their total population of 26,262,368, as of 2018 (*Madagascar | Data*, n.d.). The growth in population has been tightly tied with the expansion of agricultural land at the expense of deforestation. In the field, we saw that much of the country had suffered from deforestation. The cleared land was used for farming to feed the people, which impacted the biodiversity, but still did not provide some of the basic needs of the people like access to food loaded in micronutrients. There is a conflict between meeting the basic needs of the people and instituting conservation based policies (Kaimowitz & Sheil, 2007). Often times people and culture loose the battle to charismatic animals.

Many conservation projects maximize the presence of charismatic animals to gather financial support from donors. The Malagasy charismatic animals are said to have been around before humans arrived. When the first humans arrived in Madagascar approximately 2,000 years ago, they found a wide variety of species from large megafauna to small mammals (Hansford et al., 2018; Richard & Dewar, 1991). Lemurs had colonized the island some 40 - 50 million years ago, perhaps on a large mat of vegetation that they hopped onto on mainland Africa (Hansford et al., 2018). Today, we now observe over 100 different species of lemurs that have become specialists in their respective environments (Hansford et al., 2018; Patricia C. Wright, 2016). Several national parks have been put in place in hopes of protecting the biodiversity.

Centre ValBio (21°13’0” S, 47°25’0’’E) is a research center in Ranomafana National Park funded by many institutions across the world from Finland, the United Kingdom, and academic institutions in the United States (Duke University and Stony Brook University) (**Fig. 4**)(Patricia C. Wright, 2016). The research center welcomes scientists, artists, students, and curious people from all around the world to provide an educational space and a home to perform research projects, to learn, and educate people about the importance of the unique biodiversity found on the island (*Centre ValBio at Stony Brook University*, n.d.). The different projects that support the conservation of biodiversity come with different responsibilities: some are focused on the reforestation project, others play a role in helping the villagers around the park remain healthy, and others are involved in monitoring different lemur families.

Figure 4. Image of NamanBe which is the main administrative building facing the dormitories. On the bottom left is the amphitheater where on clear days shows take place.

During my time at Centre ValBio, in the summer of 2019, teams were sent out every day to monitor the different families of *Propithecus edwardsi* (Milne-Edward's Sifaka) and *Hapalemur aureus* (Golden Bamboo Lemur) (**Fig. 5**) (Wright et al., 2012). *P. edwardsi* was followed meticulously because their gestation period was being observed as part of a long term study (Wright et al., 2012). It is an especially interesting species because it is the largest of the 12 species of lemur found in that region. *H. aureus* was followed for two reasons. There are only two individuals left in Ranomafana National Park, a male and his daughter in Talatakely. Researchers at the Centre ValBio were preparing a translocation mission to bring other *H. aureus* in hopes of increasing the population in Talatakely. The second reason is that tourists love to see them, and so the guides need to know where they are at all times. Everybody in the Center is actively involved in the conservation of lemurs.

Figure 5. Images of *Propithecus edwardsi* (left) and *Hapalemur aureus* (right). Images taken by Nick Garbutt.

Propithecus edwardsi (in the order Primates and the family Indriidae) is native to Madagascar. Its population is endangered and decreasing, according to the IUCN (International Union for Conservation of Nature) Red List (Adriaholinirina et al., 2014). In the wild, there are currently less than 10,000 individuals left (Wright et al., 2012). *P*. *edwardsi* are found in the eastern part of the country in the Fianarantsoa province and their territory is less than 5,170 km^2. The southern tip of their range has been found to host less *P. edwardsi*. A census of the population, done from 2000-2005, found that there were no lemurs in the northern border of Ranomafana National Park, which estimates a 20% decrease in the population because of deforestation for slash and burn agriculture and hunting (Dunham et al., 2008; Lehman et al., 2006).

Propithecus edwardsi are black with chocolate brown and some have white patches on their back; for others these white patches can sometimes turn into silver hairs. There are no size differences between the sexes (Dunham et al., 2008; Patricia C. Wright et al., 2012). Their size ranges from 5 to 6.5 kg and their length is from 42 cm to 52 cm (Richard & Dewar, 1991). They are considered folivores (leaf eating), frugivores (fruit eating), and granivores (seed eating) (Hemingway, 1998). It is understood that their preferred food sources are fruits but in dryer seasons, fruits are scarce so they increase their intake of mature leaves (Hemingway, 1998; Wright et al., 2012). This type of behavior has been observed amongst many large bodied primates. *P. edwardsi* feeding behavior is closely monitored in Ranomafana National Park.

Ranomafana National Park (RNP) is a 41,600 ha evergreen submontane rainforest located in southeastern Madagascar (21°16'S, 47°20'E) (Wright & Andriamihaja, 2002; Wright et al., 2012). Its elevation ranges from 600 to 1500 m (P. C. Wright & Andriamihaja, 2002). The park is split in half by the Namorona River. Along the river sits the research station that was established in 2003, Centre ValBio (**Fig. 4**) (Wright et al., 2012). For Centre ValBio to be successful it functions like an ecosystem with many interacting parts that come together for the protection of the park by creating spaces for researchers and non-researchers from all around the world to ask questions and begin to answer them. These tools are then used to provide evidence to protect the biodiversity found in these national parks.

The Center employs 100 people that live in the nearby town in Ranomafana (*Centre ValBio at Stony Brook University*, n.d.). Projects range across a wide spectrum and are created by local people. The Malagasies are research assistants, cooks, park guides, data collectors, and various other positions that create a space for the park to be maintained and allow for the local community to be involved. For example, the medical team, led by a Malagasy doctor and Malagasy nurses, undertakes expeditions that involve educating nearby villages on the best health and nutrition practices to improve their daily life and helping the women cook meals that are high in micronutrients. The Malagasy team is suggests meals by explaining the changes to the local villagers in a respectful manner. They teach the women how to improve their meals in order to combat malnutrition among the children, while still being mindful of culture. They help each other and work hand in hand.

In 1990, Dr. Patricia C. Wright and Duke University with the help of the Malagasy government worked together to protect the rainforest in Ranomafana after she and her colleagues rediscovered the Greater bamboo lemur (*Prolemur simus*) and she discovered the Golden bamboo lemur (*Hapalemur aureus*) among 10 other species of lemurs that live there (**Table 1**) (Wright, 2016). Both *P. simus* and *H. aureus'* habitats were being destroyed due to logging that had been permitted at the time by the government (Wright & Andriamihaja 2002, Wright et al. 2012). In 1991, Dr. Wright became an associate professor at The State of New York (SUNY) Stony Brook in the

Department of Anthropology and the Ranomafana National Park was also established. The park was later handed over to the national Malagasy government's park management services, l'Association Nationale pour la Gestion des Aires Protégées (ANGAP), or the National Association of Management of Protected Areas (Wright & Andriamihaja, 2002).

Table 1

List of the 12 lemur species found in Ranomafana National Park.

Scientific Name	Common Name
Avahi peyrierasi	Peyrierasi's woolly lemur
Cheirogaleus crossleyi	Crossley's dwarf lemur
Daubentonia madagascariensis	Aye-aye
Eulemur rufifrons	Red-fronted brown lemur
Eulemur rubriventer	Red-bellied lemur
Hapalemur aureus	Golden bamboo lemur
Hapalemur griseus	Gray gentle bamboo lemur
Lepilemur microdon	Small toothed sportive lemur
Microcebus rufus	Brown mouse lemur
Prolemur simus	Greater bamboo lemur
Propithecus edwardsi	Milne Edwards' sifaka
Varecia variegata editorum	Black-and-white ruffed lemur

Ranomafana National Park is home to various species of plants, mammals, birds, reptiles, and amphibians. ANGAP has been more and more interested in exploring the interactions of these various species to create the best environment for each to thrive (Wright & Andriamihaja, 2002). By focusing on the ecosystem rather than the lemurs they realized that all the microhabitats within the park are valuable. Researchers in the RNP were interested in looking at the relationship between the cyclical patterns of the animals, plants, and climate. This study is known as phenology. They started to analyze the feeding behavior of the lemurs by solely focusing on the patterns found in fruiting, flowering, and leafing of the trees they fed on (Dunham et al., 2018).

In this thesis I explore the role that rainfall play in the process of flowering as climate patterns are changing due to global warming. Flowers serve a purpose in the diet of lemurs but they are also the reproductive system of many trees and are essential to understanding the regeneration of fruits and vegetation as a whole. An understanding of the influence that climate change may have on the systems in the rainforests could help us understand systems of vegetation and food availability for lemurs. I underscore how humans, through deforestation, have played a role in increasing climate instability and increasing food insecurity for lemurs. In looking at the data available, I hypothesized that due to climate change we would no longer be able to associate high levels of rainfall to high levels of flowering based on the flowering phenology and rainfall data gathered from 2012 to 2018.

1.2 Lemurs

Lemurs arrived between 60-50 million years ago (myr) (Poux et al., 2005). The arrival of lemurs in Madagascar is a much disputed subject among biogeographers and paleontologists. There are two competing theories for how the lemurs arrived in Madagascar: the land bridge hypothesis and the rafting hypothesis. The land bridge hypothesis argues that the mammals walked across the Mozambique channel from mainland Africa to Madagascar (Ali & Huber, 2010). In the Mozambique channel, there is a bathymetric feature, known as the Davie Ridge that goes north to south, which could have helped the lemurs cross over. It was discovered that the space required to walk would suggest that the two pieces of land were once connected. According to Ali and Huber (2010), had walking been a possibility we would have observed a larger variety of animals such as antelopes, apes, elephants and lions. However, the ecosystem would not have been able to support these larger animals. It is hard to completely discredit the walking theory because archeologists are still discovering hidden remains in Madagascar.

The second hypothesis, the rafting hypothesis (also known as the sweepstakes hypothesis) comes from arguably one of the most important thinkers in the field of paleontology in the 20th century, George Gaylord Simpson. Dr. Simpson argues that when the lemurs were moving, mainland African and Madagascar were separated, based on their estimated arrival (60-50 myr). The only animals that could do this trip were small mammals with a seasonal torpor that could get on wooden rafts for extended periods of time (Ali & Huber, 2010). Seasonal torpor allows the animal to shut down its body for an extended period of time. The missing link to Dr. Simpson's hypothesis was the lack of explanation as to which winds and currents transported the rafts to the landmass.

Ali and Huber (2010) supports the hypothesis that was brought forth by George Gaylord Simpson through paleoceanographic modeling (modeling of ocean currents). The current position of mainland Africa and Madagascar have moved 1,650 km closer to the equator. As both landmasses have shifted they have caused changes in the ocean currents. Their model shows that the strong circular water currents off the coast of the island caused the water mass trajectories throughout the region to converge. In addition, there is a strong anti-clockwise gyre (spiral), that has directed much of the flow along the African coast eastward towards Madagascar rather than southward (Ali & Huber, 2010).

During the Eocene, a series of storms and ocean current activity allowed the small mammals to transport themselves from the northeast of Mozambique and Tanzania to the north coast of Madagascar. The movement of the landmasses pushed Madagascar to an area of the ocean that experiences strong equatorial gyres, decreasing the possibility that larger mammals could have made the trip (Ali & Huber, 2010). The large mammals would be less likely to undergo seasonal torpor.

Whether the land bridge hypothesis or the rafting hypothesis is supported, there is no question that somehow lemurs made it to Madagascar and over time uniquely filled up niches in that ecosystem. The various species that arrived on the island have filled niches that were not occupied by other species, this process is called adaptive radiation.

An example of adaptive radiation is *Daubentonia madagascariensis* (Aye-aye). A lemur that filled a niche that is occupied by woodpeckers in most ecosystems (**Fig. 6**). It is one of the largest nocturnal lemurs and the only extant member of its family. Its range extends from the northern Montagne d'Ambre and Samabava, in the northwest to Sambirano, and in the south of Ranomafana and Bemaraha (Quinn & Wilson 2004) (**Fig 1**). Woodpeckers play a role in the construction of homes for other mammals by using their chiseled beaks to drill holes of various sizes into dead trees. The woodpeckers use these holes for their young, but after they vacate it becomes home for other species. This niche, in Madagascar, is filled by *D. madagascariensis*. *D. madagascariensis* in its solitary nature roams the forest at night looking for a tree filled with grubs to feed itself (Quinn & Wilson, 2004). The third and long rotating digit of the hand serves to feed and groom. The *D. madagascariensis* uses its long digit to tap against the wood and listen to the sounds of vibrations emitted by the wood to decide whether or not to begin excavation based on the presence or absence of grubs. Its diet consists of various amounts of insect larvae, fruits, nuts, and plants (Quinn & Wilson, 2004). Unfortunately, this species is endangered and its population is decreasing (Adriaholinirina et al., 2012)

Figure 6. *Daubentonia madagascariensis* (Aye-aye).
(Image taken by David Haring)

Protecting the forests, its inhabitants, and research go hand in hand. Lemurs that are endangered or critically endangered are closely followed and monitored on a long term basis to improve the species' chances of survival. Amongst the 12 species of lemurs present in the park (**Table 1**), a total of 8 species have been researched longitudinally with a focus on *Propithecus edwardsi* and *Hapalemur aureus* (Wright et al., 2012). Long term observation and analyses have allowed researchers to point out trends and continue to justify the importance of national parks in Madagascar for lemurs and other species.

The long term research has taken place in five different places across the park: Sakaroa, Valohoaka, Mangevo, Vatoharanana, and Talatakely which are all located in the southern half of the park (**Fig. 7**). Talatakely has been the site for long term research due to its status as a disturbed forest that is inhabited by a population of *P. edwardsi*. It is also the site of a 55 year (1965-2020) tree phenology study (Razafindratsima & Dunham, 2015). The patterns of these 457 individual trees, that include 69 tree species, and the ways in which they are influenced by rainfall are closely monitored because *P. edwardsi* depends on these trees for its diet (Dunham et al., 2018).

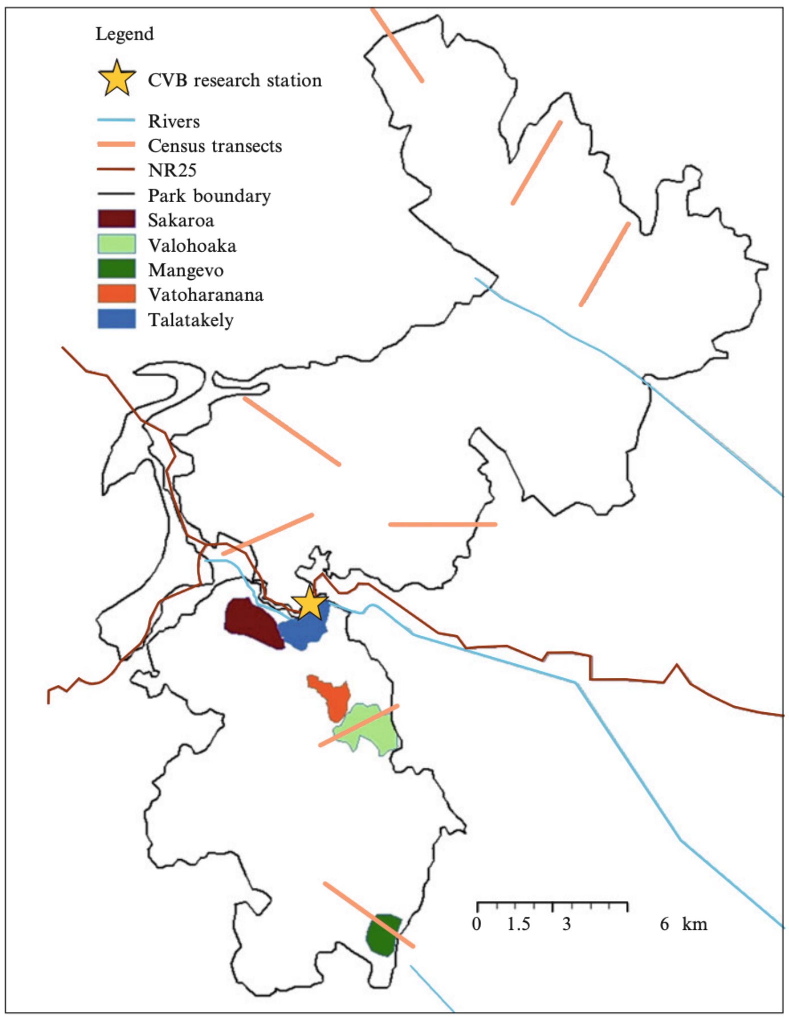

Figure 7. Map of Ranomafana National Park in the Southeastern part of Madagascar showing the active research sites (Wright et al., 2012).

One of the most striking aspects of natural history is that of patterns of flowering, leafing, and fruiting that happen because of various fluctuations within abiotic factors, such as air temperature, rainfall, light availability, and soil composition. Recent observations have shown that these fluctuations are being challenged by anthropogenic changes and our natural cycles could suffer from it (Dunham et al., 2008; Hansen et al., 2006). Various explanations have been attributed to the changes in patterns that were once deemed fairly stable and predictable (Dunham et al., 2018).

Understanding the link between plant phenology and its relationship with abiotic patterns allows us to create better conservation strategies for both the wildlife and the vegetation that depend on these patterns (Dunham et al., 2018). The article, “Flowering phenology and diversity in tropical Bignoniaceae,” focuses on the Bignoniaceae family by giving insight on the evolution of plant phenology to further facilitate pollination, through bees and bats, in the tropics by different organisms (Gentry, 1974). Through the research, the interdependence of the Bignoniaceae family and the bees and bats has furthered the understanding of the ecosystem in ways that were not considered before. This has allowed scientists to establish efficient conservation strategies for each respective species.

More recently, Zhang et al. and Dunham et al. have started to look at the impact that climate change has had on forest. In China, researchers observed the impact that extreme climate events in Macau have had on the temperate forest (Zhang et al., 2018). They concluded that due to extreme climate events the mean flowering period for the 12 species studied had shifted to being between the spring and summer (Zhang et al., 2018).

In Talatakely, Ranomafana National Park, researchers compre fruiting patterns to precipiation. Dunham et al. (2018) found that less rainfall in the dry season led to later fruiting over the next 12 months. Despite the change in climate and the slight shift they were still able to associate high levels of rainfall with high levels of fruiting.

By observing rainfall and air temperature, abnormal changes in climate have been highlighted. The implications of these changes are unprecedented (Hansen et al., 2006). It has been estimated that some ecosystems in Africa will experience an increase in rainfall while others will face an increases in droughts. For example, the Congo Basin is expected to experience an increase in wet weather, whereas west equatorial Africa should expect an increase in dry seasons (James et al., 2013). Vegetation is highly influenced by the rapidly changing patterns and influences the ways in which the animals respond to these patterns. Experts have established that these changes could have negative impacts on sensitive species with small territories (Butler, 2018; Hansen et al., 2006). The chances of predicting the timing of the biological events found in both the flora and fauna will become increasingly difficult or nearly impossible if climate becomes more variable and unpredictable.

Climate research in Madagascar has shown that changes in climate has had an impact on phenological patterns. The longer dry seasons and more frequent El Niño events have had an impact on the lemur populations in Ranomafana National Park (Wright et al., 2012). Wright et al. (2012) describes particular hot seasons in the month of November over three years (2007, 2008, and 2009) that appeared to exceed 30°C . The researchers thoroughly describe the impacts of the irregular periods in which the island experiences ecological damages within the ecosystem and specifically describes its impact on the *P. edwardsi* reproductive rates (Dunham et al., 2008). El Niño events impacts the food availability, reducing the amount of fruits available for lemurs that year (Dunham et al., 2018). The impact in food availability threatens their gestation period and their ability to feed their young (Dunham et al., 2008).

Researchers in Kibale National Park, a rainforest in Uganda, compared the flowering and fruiting phenology in two parts of the site to the abiotic factors like rainfall, temperature, and light availability (Chapman et al., 1999). They mostly concluded flowering specifically was quite variable but in general, species seem to be fruiting at the start of the dry season (Chapman et al., 1999). Similar variable patterns were found in the fruiting phenology of Ranomafana National Park (Dunham et al., 2018). Although flowering and fruiting are not the same they are related to each other and one leads to the other.

One night at the Centre ValBio during one of the many lectures we attended, Dr. Wright told us that in the very beginning of the conservation journey she was focused solely on the lemurs. Then she quickly realized she could not disassociate the lemurs from their environment and so she had to consider other things like the forest in which the lemurs live and the nearby villages. In understanding the forest system and its relationship with the ever changing climate, we can further improve our understanding of farming systems that are so closely tied in Madagascar to the forest. This research attempts to do the second half of the job, which is focusing on flowering to put the piece together to further the conversation on the conservation of the park and its inhabitants. This conversation is only valuable if people are included.

1.3 People

It is hard to talk about lemurs and their presence in the forest without discussing extensively the role that humans play. They use the forest for their livelihood but they can also help build and maintain the forest. Habitat destruction is the number one threat to lemurs, specifically through deforestation (Dunham et al., 2008). The local people can play a helpful role in regards to the conservation of the forest, as is seen in Centre ValBio. In this next section of the thesis, I elaborate on the nexus among people, lemurs and climate change.

One of the first lectures I attended with my peers during the field school, in Antananarivo, was by Dr. Benjamin Andriamihaja, geologist and executive director of the Madagascar Institut pour la Conservation des Écosystèmes Tropicaux (MICET) on the rapid deforestation of the country. He gave us an overview of Madagascar's geology and its ecoregions. Dr. Andriamihaja emphasized the mass deforestation that had taken place over the past years. The most shocking was the rate at which the various forests were being lost and the reasons behind their loss.

Madagascar has lost nearly 90% of its rainforest, as the flora has been cut down due to *taavy* (slash and burn agriculture) and other unsustainable farming practices (Moser, 2008; Tyson, 2013). *Taavy* is a farming technique where the farmer cuts down the vegetation of a targeted area for farming and burns it down for about 3-5 years (Moser, 2008). Other farmers will use mountainous areas to create terraces for rice fields.

This traditional method of farming has been just as destructive to the natural habitat as has French logging in the past and cash crop farming during colonialism and current logging done by Chinese companies (Moser, 2008). These factors have significantly contributed to the dismal state of the island. Whether mass deforestation was adopted pre- or post- colonialism, it still remains an issue, primarily because these practices are not regulated. People will often perform slash-and-burn agriculture anywhere in the rainforest. Soil found in the rainforest is not compatible with long term farming which means that as time goes by and the nutrients are stripped away from the land, the farmer is forced to find another location in order to continue (Allnutt et al., 2013).

The government has tried to address poverty by instilling responsible logging techniques and vowing to better protect its national parks to preserve what is left of the biodiversity at the World Parks Congress in 2003 by addressing deforestation head on (Moser, 2008). Despite the vows made to the international community, the forest of Madagascar still contains important types of woods that are used to trade. For example, trade records have shown the exporting of Rosewood from Madagascar to China has benefited the Malagasy economy (Moser, 2008). China, like in many other African countries, is a major consumer of this natural resource (Allnutt et al., 2013). This study shows that the government's effort to decrease deforestation has not been successful throughout the country. A survey done in one of the largest protected areas, Masoala National Park in the northeastern part of the country, showed that there was a slight increase in deforestation from 2005-2008 (0.99%) and even more from 2010-2011 (1.27%) (Allnutt et al., 2013). The rates of deforestation cannot be generalized to all of

Madagascar because not every region was monitored over this period of time and not every region has the same population density, regardless of the general exponential increase (Allnutt et al., 2013).

The population is increasing at a rate of 2.75% and as it grows the demand of farming land increases, which also increases deforestation (*Madagascar | Data*, n.d.; Tyson, 2013). People need to eat. I previously mentioned, visiting a Tamale village where one of the King's biggest concern was food availability for now and the future. But often times food availability for humans is synonymous to deforestation that results in habitat destruction for lemurs. Madagascar struggles to find the balance between protecting its natural habitat for lemurs like *P. edwardsi* and filling the gap of poverty. The root problem of both groups lies in food availability. The phenology data that has been collected to monitor the feeding of *P. edwardsi* is in itself important to solely understand how systems of vegetation are changing as climate change escalates.

Habitat destruction and climate change lead to shifts in geographical ranges. This shift tends to happen to animals that are very niche specific. Once an animals habitat is destructed it moves to the next geographical range. As the temperature changes, animals tend to move up their geographical range in order to live in conditions that allow them to thrive (Brown & Yoder, 2015). Brown and Yoder (2015) used a predictive model to see how much the geographical ranges of the lemur would change in the face of climate change. They predicted that 34 of the 57 species that they examined will face a huge reduction of their range in the upcoming 70 years as temperatures continue to increase slowly. Nine out of the 57 lemurs were predicted to expand their range and 13 would remain stable (Brown and Yoder 2015). Habitat destruction and climate change are both challenges that are anthropogenic (changes driven by humanity). They challenge and play a role in the population of *P. edwardsi* but they also challenge environments that humans live in.

1.4 Climate Change

Climate change has been attributed to anthropogenic activity around the world. According to the Intergovernmental Panel on Climate Change (IPCC), temperatures have increased reaching approximately 1°C since the start of the Industrial Revolution times and this has been increasing at a 0.2°C every decade (*Global Warming of 1.5 °C —*, n.d.). The increase in temperature is due to an increase in the carbon dioxide in the atmosphere. More carbon dioxide has led to an increase in photosynthesis, changing plant productivity (Forkel et al., 2016). This indicates that climate change could have an influence on phenology, vegetation physiology, and vegetation dynamics.

Madagascar is especially vulnerable to changes in climate because of its geographical location as an island. Climate change has the potential to polarize Madagascar's experience with climate, which has been highlighted with more cyclones and longer dry seasons(Dunham et al., 2008, 2018; Wright et al., 2012). Cyclone events are part of Malagasy weather cycles; they happen from December through April, which is during the gestation period of *P. edwardsi* (Dunham et al., 2008). The passage of a cyclone, depending on its strength, often removes leaves, flowers, and fruits from trees. Some cyclones will leave some trees with no fruit at all which is dangerous for the *P. edwardsi* during its gestation period (Dunham et al., 2018). This reduces food availability during that period. *P. edwardsi* is an example of the effects that climate change has had on lemurs through the passages of cyclones it has reduced food availability for certain years and decreases in their reproduction.

Long-term research, on lemurs, has shown that decreases in the lemur populations could be due to the drought periods, habitat destruction, and El Nino Southern Oscillation (ENSO) events (Dunham et al., 2008). Dunham et al. (2008) remarks that the change in the patterns of weather were once obvious but now no longer are. Dry seasons have become longer and cyclones much more frequent. Three years were marked to have had temperatures above 30°C : 2007, 2008, and 2009(Wright et al., 2012)

Drought redistributes the available resources for that specific period of time and may even impact the vegetation and lemurs. During warmer and dryer years *P. edwardsi* loses infants and rainfall levels impact the reproductive rates (Wright et al., 2012). Research has found that there was a negative correlation between fecundity during gestation period and number of cyclones in the same year. In other words, the more cyclones there were the less fecundity there was(Dunham et al., 2008). Unfortunately, the paper does not elaborate on the strength of this correlation. *P. edwardsi*'s hormones (cortisol) were measured during the ENSO years and it was found that cortisol levels were highest during ENSO years (Dunham et al., 2008). The stress hormone, cortisol, appears to be elevated during the dry season because lemurs struggle to find food which impacts their fecundity (Wright et al., 2012).

This project attempts to understand the new patterns that are formed as climate change escalates and looks at flowering phenology related to rainfall as a means to measure that change. Flowering phenology is also used to understand the ways in which vegetation will change and how that will influence food availability for lemurs. I hypothesize that climate change continues to change the rainfall patterns, we would no longer be able to associate high levels of rainfall to high levels of flowering based on the flowering phenology and rainfall data gathered from 2012 to 2018.

Methods

Ranomafana National Park (RNP) is located in the southeastern rainforest belt of Madagascar and it covers 41,600 ha ranging from 500-1500 m in elevation (Dunham et al. 2018). The site was set up in Talatakely near RN 25 (the main highway in Madagascar). Talatakely is a protected secondary rainforest recovering from selective logging between 1986-1989, referred to as a disturbed forest throughout this paper (Wright et al. 2012). The selective logging, often of the large fruit trees, led to the introduction and spread of invasive species such as *Psidium cattleyanum* (Chinese guava or Strawberry guava) and *Rattus rattus* (Black rat). A large part of *Propithecus edwardsi*'s diet is fruit but they also consume flowers and leaves to supplement their diet (Hemingway, 1998). The selective logging, also a form of deforestation and another way in which humans have influenced fruit availability for the *P. edwardsi*. *P. edwardsi*'s diet mostly consists of fruits that are found during high levels of rainfall and during low levels of rainfall it will supplement its diet with leaves. The analysis of the long-term rainfall and temperature database in Centre ValBio has shown that dry seasons are now longer and cyclones happen more often (Wright et al. 2012). The peak wet season tends to occur between January and March and the dry season is often between June and October (Dunham et al. 2018). All the data used in this thesis were collected from the ongoing research projects that are taking place in Ranomafana National Park.

2.1 Rainfall Data

The Tropical Ecology Assessment and Monitoring (TEAM) program started by Conservation International was set up as a means to create a more homogenous method of gathering data related to biodiversity. Their goals are to monitor the forests, to make climate data available to a wide variety of scientists that need it, and to improve the management of protected areas. As part of this effort, a station was set up in Ranomafana National Park across from the Centre ValBio at the top of a hill. The site has been collecting temperature, atmospheric, and precipitation data every 5 minutes since 2011.

Prior to this, collecting data on the temperature of the rainforest was decentralized, but having it near the park now allows the monitoring of the microclimate found in Ranomafana. I used the rainfall data from 2012-2018 from the TEAM program for my analysis. I chose to begin the analyses with data from 2012 because it was the first full year of data that was collected. I could then compare the monthly sum of rainfall per month over seven years (2012-2018) and evaluate that data with respect to flowering over that same time period.

2.2 Flowering Data

The phenology team at Centre ValBio has been monitoring tree species since 1986. Their dedication to the recording of the data has played an immense role in understanding the feeding and breeding behaviors of lemurs and also to monitor the areas in which they live. The data are from an ongoing 55 year study that monitors 457 individual trees, 69 tree species that were picked on the trails based on the consumption of the lemurs (Dunham et al. 2018). The trees were chosen randomly in the forest among the common resources that lemurs consume.

The phenology team gathered data on flowering, fruiting, leafing, diameter of the tree at breast height (DBH), and the general monitoring of the plants (assessing whether the tree is alive or not, and looking for any potential diseases). The teams go out every month to monitor trees that were picked on trails based on their consumption by the lemurs. As previously mentioned, I focused on flowering for my research. I was able to go out with the tree monitoring team during the month of June 2019 for one of their sessions. I examined the presence or absence of flowers (buds or fully formed flowers) and related it to rainfall and then air temperature. The raw data for the flowers was collected on a scale of 0 to 5, 0 being no buds or flowers, and 5 being all if not most branches have flowers or buds. Instead of using the numeric scale as recorded in the field, I re-coded the data into a binomial: the presence of flowers was represented by 1-5 or absence of flowers was represented by 0. The data was dichotomized because many flowers are missed during the survey, specifically those at the top of the canopy.

2.3 Statistical Analyses

A variety of statistical analyses, conducted using the Software RStudio, were used to address the two part of the hypothesis and several ancillary analyses. All the statistical analyses were done using the Software RStudio. A correlation was used to evaluate the hypothesis. In addition, to evaluate the hypothesis, I conducted a variety of supplemental analyses. The first part looked at the overall precipitation over the 7 years and then the overall air temperature. I used a box plot to observe the spread of the monthly sum of rainfall (mm) over the 12 months of the year to compare it to the base line that was established by Dunham et al. (2018) in their most recent analyses and Wright et al. (2012) in her long-term analyses of the climate of the park. The second part uses circular statistics to show the month of the year when the greatest number of tree species is flowering. To assess the hypothesis, Pearson's correlation analysis was performed to determine whether there was a relationship between the monthly sum of rainfall (mm) and the presence of flowers. This would allow me to see if high levels of precipitation correlate with high levels of flowers and if low levels of precipitation correlate with low levels of flowers.

Results

When looking at the data from 2012-2018 it is evident that there is a cyclical pattern found within the rainfall (Fig 8). The highest periods of rainfall are found in the months of January and February and lowest in September, with outliers in May, October, and December. November specifically had a low and a high outlier, indicating an extreme period of dryness that was out of the ordinary and one of wetness that was also out of the ordinary during those few months (Fig 8). Indicating the cyclical nature of rainfall.

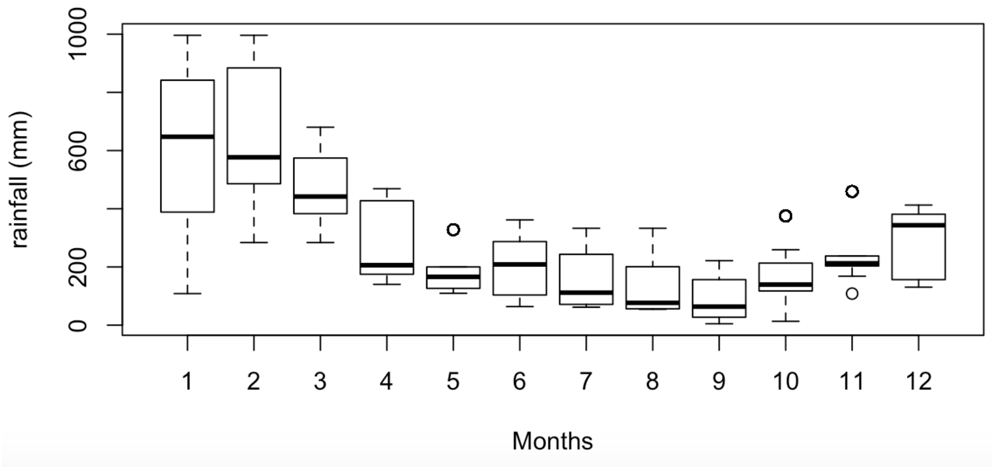

Figure 8. Average monthly rainfall in Ranomafana National Park shows the variation between the rainy season and dry season (2012-2018).

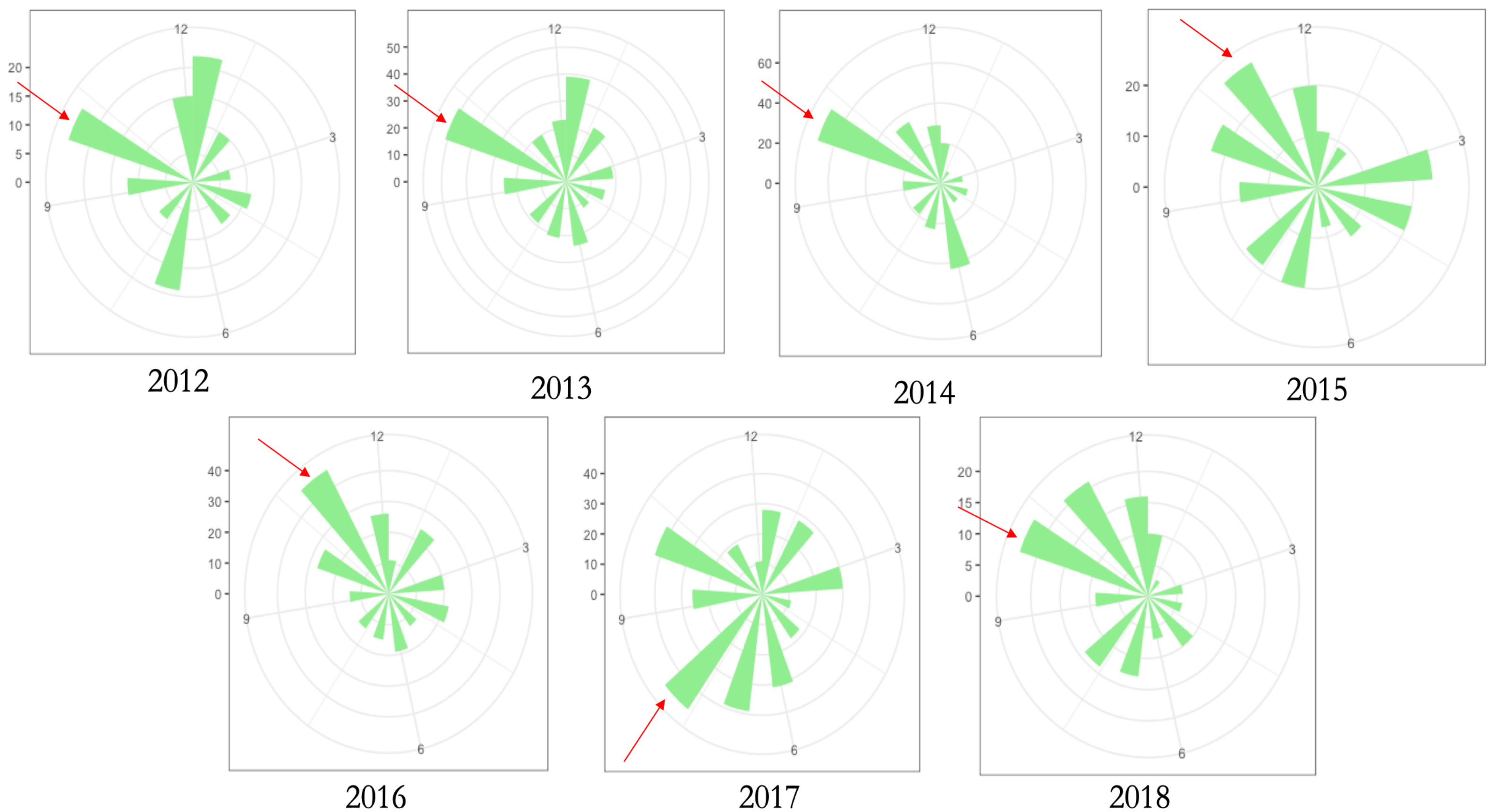

Figure 9. Graphical representation of flowering distribution of each month (A-F). The circular graph is red like a clock (1= January and 2=December) (2012-2018). The scale on the right represents the total number of trees that had flowers during that month. The red arrows indicated the months with the highest number of trees with flowers.

In 2012, the most flowers were observed in the month of October, closely followed by that of January and July where both of the amounts of flowers present ranges from a total number of 15-20 flowers and buds observed by the team (**Fig. 9**). In 2013, the month with the highest number of flowers was also October but then the flowers ranged between 40-60 total number of trees. In 2014, we see more flowers are recorded a month later in November and more flowers were observed in the month of June. During 2015, the month of November had the highest total number of flowers as well, closely followed by March and they both fell in total number of trees with flowers. In 2016, the highest amounts of flowers were observed in the month of November and the flowers observed range from 30 to 40. In 2017, we do not see the pattern observed in the other years with peak flowering in October and November. In 2018, the pattern of flowering returns to having the highest number of flowers found in October closely followed by the month of November. The numbers of flowers present range between 15 and 20 (**Fig. 9**). To summarize, in 2012, 2013, 2014 and 2018 October was the month with the highest total number of trees with flowers. In 2015 and 2016 November was the highest total number of trees with flowers and lastly in 2017 September had the highest total number of trees with flowers.

For each tree over 7 years, Pearson's correlation between the sum of the monthly rainfall and monthly flowering is a negligible negative correlation and it is not statistically significant, $r(N = 28{,}024) = -0.0086$, $p = 0.26$. Whether or not a tree had flowers did not differ significantly by the rainfall that m

Discussion

In the first part of the statistical analyses, I analyze the overall trends of the total monthly rainfall during the years of 2012-2018. Madagascar's wet seasons during the years of 2012-2018 are in correlation with the baseline trends that were established in Wright et al. (2012) and Dunham et al. (2018). On the baseline, January through March are months of high rainfall averages that were reflected in my analyses as well. During these seven years, Madagascar has experienced four cyclone events: Giovanna in 2012, Haruan in 2013, Enawo in 2017, and Ava in 2018 (Dunham et al., 2018). These moments of increases in the precipitation did not influence the general trend of rainfall that was captured by the Tropical Environment Assessment Management (TEAM) at the Centre ValBio but it is in line with the long-term rainfall database that has been collected explaining that cyclones happen more often.

According to the baseline from Wright et al. (2012) and Dunham et al. (2018), Madagascar's dry season happens during the months of June through October. In 2012-2018, May through October had the lowest monthly average rainfall. The long term research performed at the center ValBio discusses the lengthening of the dry season but has not pinpointed which months are influenced (Wright et al., 2012). In these analyses we see that over a period of seven years May is consistently low, on average, suggesting that May could be potentially added to the dry season in the coming years as we continue to observe the years of rainfall. There is a clear lengthening of the dry season. It is important to note that there was a historical drought in 2015 especially accounted for a low month of precipitation in the month of May (Dunham et al., 2018).

In testing my hypothesis, I observed whether high levels of flowers observed on trees were correlated with high levels of rainfall. The circular statistics data is a visual representation of the flowering presence over the twelve months between 2012-2018. I observed the total number of trees tended to happen in the months of September, October, and November with four out of the seven years happening in October. In contrast to the literature on flowering phenology, my analyses shows that moments when high levels of flowers are not associated with the high levels of rainfall during the months of January through March. If anything they fall closer to the dry season (May through October). This conclusion is also seen through the results of Pearson's correlation between rainfall and flowering.

I examined the relationship between presence of flowers with the average monthly rainfall where each tree observed is the unit of analysis. There is no correlation between flowering and either of the two variables. The correlation between the sum of rainfall and flowering across the seven years amounted to a negative negligible correlation that is not statistically significant. When comparing the lack of or presence of flowers to the temperature we see a similar pattern where no correlation is seen.

The literature shows that there have been associations of the high levels of flowering, fruiting, and leafing in phenology have been associated with high levels of rainfall but it also underscores that changes have been observed. Hemingway (1998) describes the association between high levels of leafing and flowering to high levels of rainfall in the primary forest section of the park. Hemingway's work offers a plethora of questions that need to be further analyzed when discussing the role that rainfall plays in the tree phenology in Ranomafana National Park. What are the abiotic differences that we note between a primary rainforest and a secondary rainforest? Dunham et al. (2018) also describes high levels of fruiting associated with high levels of rainfall in the secondary forest of Talatakely, while underscoring the changes that we have observed in Madagascar's precipitation and air temperature change.

The cyclical and seasonal timing of flowering are related to the growth of the forest and a change in that timing threatens *Propithecus edwardsi*'s food system. Flowers are reproductive systems that play a role in the replacement and growth of the forest. Flowers are both a source of food themselves and develop into the fruits that are particularly important for the lemurs that depend on the fruits to feed their young. *P. edwardsi* depend on flowers to complement their diet but they also depend on flowers to produce fruits in an indirect way to complete their diet (Hemingway, 1998). It is through the availability of food that mothers can care for their young

Propithecus edwardsi's food systems is not just threatened by the abiotic cyclical and seasonal timing, it is also endangered by deforestation. Although climate change has an influence on the availability of food, people too have played their role in influencing that structure put in place. Deforestation is a huge manmade and driven phenomenon that is perpetuated by larger corporations and local people wanting to farm for their own livelihood. This dynamic was illustrated in Talatakely where selective logging of the larger fruiting trees that *P. edwardsi* feeds on took place. Wright et al. (2012), in the long term study describes that females in the primary forest (not disturbed) weigh more than females in the secondary forest (disturbed) and therefore have a higher reproductive success. Deforestation remains an issue in Madagascar as it continues to drive a wedge between the wildlife there and the people.

Madagascar's top priority is to protect its level of endemism while still respecting its local populations. One was to start to find the balance is to begin to understand the changes in rainfall. As the rainfall levels continue to change I would urge future work to explore whether some of the patterns that we have established are still relevant and exploring that through different statistical methods. La Selva Biological Station, a research station in Costa Rica similar to Centre ValBio, explored the mysteries behind flowering phenology in their tropical rainforest. It was clear for them that the topic was more complex than it appeared and they suggested rather than using various numerical forms of analyses to understand when and how flowering happens we need to use a visual medium. In doing so, we would be able to see the variations that happen in the rainforest (Hartshorn & Hammel, 1994). Patterns of flowering may actually depend not on the month in which those flowers are observed but rather what happened weeks/months earlier.

The lack of relationship between rainfall and temperature supports some previous studies that have explored the role of abiotic factors in the piece of the puzzle (Hartshorn & Hammel, 1994; Omondi et al., 2016). These studies were performed in Costa Rica and Kenya that have explored flowering phenology in various aspects. Hartshorn & Hammel (1994) have explored how the extension of the photoperiod can influence flowering, fruiting, and leafing. In this case, it would only be relevant for the flowering. An appropriate site of comparison would be La Selva Biological Station in Costa Rica. The only difference is that their trees are more based on old growth trees compared to the newer growth of trees that is found in Ranomafana National Park where the research is centered.

Particularly with the fact that much research (some done in Costa Rica) have tested the amount of light and soil composition and its influence on the flowers instead of temperature and rainfall (Hartshorn & Hammel, 1994). Although both play an important factor they have found that light has a greater impact on flowers. Past studies have shown that the amount of light a flower gets can have a larger impact on when and if the flower does appear (Bunt et al., 1981; Hartshorn & Hammel, 1994). I would advise that the Ranomafana National Park considers measuring light in the future to further improve their abilities to understand the ever changing phenology, as is done in La Selva Biological Station in Costa Rica. In addition, we can start to see which fruiting trees thrive the best and adapt to climate change. This can in turn inform selective logging practices and help accommodate for farming practices if we understand the links between flowering, rainfall, and iridescence.

I would also put in question the length that I used to discuss the changes in climate. How long is long enough to consider a change in pattern? In a seven year data set, we are able to see the lengthening of the dry season through the month of May. Small patterns noticed over a shorter period of time should serve as alarm calls. I would recommend observing the data more closely by looking at years that experienced extremes in temperature and lengthen the research done. to separate the data by year to look at each year individually and conclude if indeed we are seeing an increase in the dry season. Longer dry seasons would suggest that there could be an issue with the development of the flowers because high periods of flowers have been associated with high periods of rainfall.

Much of the efforts done to understand how climate variability alters tropical forest phenology when looking at both the flora and the fauna have been limited to the Amazon basin (Dunham et al., 2018). Researchers should push for a global long term understanding of flowering phenology in various forms: numerical statistics, visual statistics and through the humanities. This would give us an understanding of the reproductive systems of forests to evaluate how they are changing amidst more cyclones and an increase in the length of the dry season that influences both lemurs and people.

Madagascar is not a phenomenon of climate change, it is a pattern. Its status as an island makes it even more vulnerable to changes that are in the horizon. These changes have been noted through the data that I analyze in the lengthening of the dry season more recently. As the weather is expected to become more and more unpredictable we have to foresee the changing of terminologies like phenology that are rooted in the idea of pattern. Can we refer to phenomena of this nature if they are not happening in a sequence that we expect? How do we begin to rethink and remodel the ways in which we understand patterns in nature with the changing abiotic factors in order to better understand the feeding patterns of the lemurs directly associated with these plants? In addition, we can improve their growth by understanding them in order to improve and better monitor their growth within the forest.

The results discussed here leave us with more questions and an urge to continue asking questions about the changing flowering phenology of Madagascar. It is urgent that we push to look into Madagascar as a whole to see if the changing patterns are solely something that we see in Ranomafana National Park or all of the forests in Madagascar are experiencing changing in their flowering phenology.

Conclusion

To conclude, increasing variability in relation to climate change that we are witnessing around the world will influence phenology both in the flora and fauna. The case of Madagascar is even more crucial and special attention needs to be brought to it due to the fact that it is an island with high biodiversity and high endemicity (Dunham et al., 2018). It is more vulnerable to slight changes that can lead to a collapse of an ecosystem if not addressed within an appropriate time period. Evidence shows that the changes in climate will have an impact on the geographical location of many species that will be forced to shift their range (Hansen et al., 2006). My research attempts to pinpoint where and which aspect of the flora will be influenced by climate changes by testing the impact of rainfall and temperature on flowering phenology of the different tree species.

I examined the relationship between precipitation and temperature and flowering as well as rainfall and flowering in order to better understand the flowering phenology of Madagascar. The results supported the hypothesis, I was not able to find a significant correlation between flowering and either monthly average temperature or monthly sum of rainfall. Past research and present work on flowering phenology continues to urge researchers to think outside the box to perform many of these analyses. One way is to observe the data using a visual model. The other way is to consider abiotic factors such as moisture in the air, soil composition, and light (Bunt et al., 1981; Hartshorn & Hammel, 1994; Omondi et al., 2016). Sunlight has also been shown to play a role in starting the flowering process. I would suggest that this study can be improved by ameliorating data collection techniques on various levels. The TEAM dataset would need to include iridescence in their data collection which would allow us to compare sunlight availability to the amount of the flowering, adding another dimension to my proposed hypothesis.

A technique should be considered as technology becomes more and more sophisticated is that of drones. In the field with the phenology team, we used binoculars to assess the taller trees and our direct sight for the smaller trees. There are limitations to both techniques but a use of both drones and eyesight could further increase our visibility for flowers in taller trees influenced by the direct sunlight. In addition, flowering phenology research is crucial for our understanding of the nutrition of all organisms and has not been updated for several years. Its update is crucial to get a more comprehensive view and elaborate solutions for the conservation of ecosystems. As data because more nuanced we need to have the right to pick out what happened in the past and predict what might happen in the future. A Malagasy proverb says, “Like a chameleon, one eye on the future, one eye on the past.” The proverb informs us on how we must treat phenology data.

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