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## An environment up in smoke?: Evaluating the effects of fire management practices on red-backed fairy-wren habitat usage

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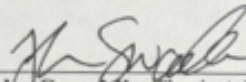
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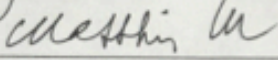
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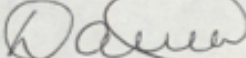
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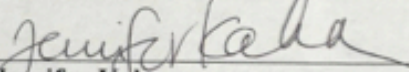
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## I. Abstract

Fire plays a significant role in shaping the environment and subsequently wildlife behavior within tropical savannas of the Northern Territory, Australia. According to previous studies, the red-backed fairy-wren (*Malurus melanocephalus*, RBFW), an endemic passerine, is negatively affected by fire. However, specific factors behind this unfavorable impact remain relatively unknown and unexplored. This study further investigates the site-specific effects of fire management on RBFW habitat usage at Coomalie Farm in Batchelor, NT. Vegetative heterogeneity and fire severity are analyzed using occurrence modeling to determine the effects of vegetation parameters and fire severity on RBFW occurrence. Interviews with Australian individuals involved in fire management were also conducted in order to gain an understanding of fire management practices in RBFW habitat and how they may differ between individuals. By combining methodologies, one may understand that both species-specific and human-related factors can be applied to issues such as fire management to gain a more comprehensive analysis that more accurately reflects interactions within an ecosystem. The study illustrates that consistency in fire management practices, collaboration between groups, and other practices are necessary to maintain an ideal mosaic habitat crucial for RBFWs and likely other native wildlife. Potential future directions in fire management within RBFW habitat are also explored.

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## 1. Introduction

Ecosystems in the tropical savannas of Northern Australia are well known for their highly adaptive and diverse nature, especially in relation to fire. An average of 350,000 km<sup>2</sup> of Australia's 1.9 million km<sup>2</sup> savannas in the Northern Territory are burnt annually, with most of these burns consisting of severe, extensive and human-induced activates during the dry season (Fitzsimmons et al. 2012). The prevalence and wide extent of fire over tropical savannas encourage the adaption of populations to these events throughout the landscape, thereby creating a varied environment with high species biodiversity.

While natural, lightning-induced burns arguably do not compose most fires presently, they also occur to a wide extent and have caused many evolutionary responses in native flora and fauna for millennia (Russell-Smith et al. 2003). Many species even thrive under burnt conditions (Russell-Smith et al. 2003). However, other species are negatively affected by fire and do not thrive under such disturbed conditions (Murphy et al. 2010). Fires vary in their severity and this, in turn, is influenced by the spatial variation of vegetation in the area, or “vegetative heterogeneity” (Johnsson et al. 2011; Garcia et al. 2011) These two factors (fire severity and vegetative heterogeneity) are not the only defining variables of species response to fire; yet, they are absolutely key to the welfare and ultimately the survival of many organisms in savanna environments (Garcia et al. 2011; Keane et al. 2012). Fire severity may directly impact the life of an organism by forcing it to relocate or causing it physical harm through burning, and it may also indirectly affect organisms by altering the resources (*i.e.* food, shelter, protection from predators, etc.) available to it. Vegetation is often the source of these resources, if not the actual resource itself; therefore, fire severity affects both individual organisms and vegetative heterogeneity, which consequently affects species abundance and biodiversity.

The past 50,000 years of Australia's human occupation and land management historically support the long and major impact of fire severity and vegetative heterogeneity (Lewis 1989). Changes in the severity of fires and the amount of vegetative heterogeneity have the potential to affect the behaviors and livelihoods of many endemic species, including birds in particular. For example, Mallee emu-wren (*Stipiturus mallee*) populations consist of habitat-specialists that primarily live in mallee-Triodia vegetation; therefore the populations of this species are threatened with local extinction when this vegetation is destroyed by fire (Brown et al. 2009). Similarly, fires in the Western United States are often documented as negatively affecting many avian species and entire ecosystems (Vale 2002). Few studies conducted on Australian birds demonstrate how birds can benefit from the effects of fire in savannas. However, there is evidence of such positive effects in other parts of the world. In the grasslands of the Serengeti in Tanzania, one study showed that bird species richness and arthropod abundance increased after fire disturbance while bird abundance amplified due to a change in grass structure that made food more accessible (Nkwabi et al. 2011). Even in the Western U.S., there are more current studies that show fire having positive implications for many birds (Vale 2002). Interestingly, these benefits often relate to changes in fire management practices.

Human diversity and the various roles that people serve in fire management strongly influences ecosystems by determining the amount, severity, and intensity of fires by altering landscapes using fire (Kohen 1995). This may in turn affect different species in varying ways, adding even more complexity to an already incredibly dynamic environment.

Humans, wildlife, and landscapes all inevitably intersect to affect fire management in this harsh yet productive and species-rich ecosystem (Williams 2002). Therefore, I advocate for an interdisciplinary approach to understand the effects of fire and its management on species by

introducing a case study of one particular avian species in the Northern Territory of Australia and its relation to fire-affected landscapes. In this interdisciplinary analysis, my goal is to understand the interaction between land management, vegetative heterogeneity, and fire severity by following a holistic approach that draw from both the anthropological and biological disciplines. Using the red-backed fairy-wren (*Malurus melanocephalus*, RBFW), a species often cited for being negatively affected by fire, as the focal organism, I address three main research questions: 1) How is RBFW occurrence in a landscape affected by changes in fire severity and vegetative heterogeneity?, 2) How does fire management vary among individuals and groups of people throughout RBFW habitat?, and 3) How might past and current fire management practices affect RBFWs? The study culminates in suggestions as to how tropical savannas can be managed to benefit the RBFW, and also how these recommendations may apply to other savanna habitats around the world.

### **1.1. ROLE OF FIRE IN TROPICAL SAVANNAS**

Australian tropical savannas are traditionally defined by their distinct seasonality and eucalyptus-dominated landscape. The monsoonal wet season experiences between 400 and 2,000 mm of rainfall a year during the summer months of November to April, while the hot dry season experiences little to no rain (Williams et al. 2002).

**Figure 1a. Dry season vs. wet season:** Same Road in Wet Season (*left*) vs. Dry Season (*right*) in Batchelor, NT



(Photo Credit: Samantha Lantz)



(Photo Credit: Kelly O'Toole)

Hardy, wide-ranging eucalyptus tree and woody shrub species comprise an average of 80% of tropical savanna vegetation, and most of the landscape may be characterized as open grasslands (Russell-Smith et al. 2003).

While the above characteristics typify Australian tropical savanna, climate and vegetative diversity and spatial layout may regionally and temporally. Some years may experience more or less precipitation, and some regions may have more open grasslands while other areas may consist of patchier eucalyptus forests. Temporal and spatial variation of regional climate and vegetation can determine the abundance and extent of fires. Fire is a constant blessing and a threat throughout tropical savannas. Essentially, typical tropical savanna climate makes a consistent fire routine possible and its biology makes it inevitable (Pyre 1991).

The seasonality of tropical savannas largely determines the temporal and spatial extent of fires throughout the landscape. Observing the stark physical differences between typical scenes of both wet and dry seasons explains and partially determines seasonal differences in fire behavior (Fig. 1a). The wet season creates an abundance of lush, green vegetation, much of

which replaces what burned in the previous dry season. High levels of precipitation from constant incoming storms and water-retention in plants during this time of the year prevent large fires from occurring (Murphy 2010). On the other hand, a lack of precipitation combined with a large buildup of vegetation accumulating from the previous wet season creates sizeable amounts of fuel for fire, especially late in the dry season (Murphy 2010).

While fires are often only perceived as a destructive force, their regenerative nature makes them a crucial occurrence in tropical savanna habitat. Burning ultimately stimulates biomass production. Burned sites exhibit on average a biomass production of 5-10% more than that found in unburned sites (Pyre 1991). Fire is shown in several studies to increase biodiversity in tropical savanna habitat within the Northern Territory (Anderson et al. 2005; Clavero et al. 2011). Furthermore, a lack of fires for an extended period of time may be more harmful to an ecosystem than having fires burn through a landscape on an annual basis (Woinarski et al. 2004; Clavero et al. 2011). The necessity of fire for the survival and productivity of eucalyptus trees and woody shrubs is evident in their reproduction. Without fire, eucalyptus trees would not be able to survive. As pyrophytes, eucalypts actually require fire in order to activate the coats of their seeds, which is necessary in order for them to germinate and grow into trees (Pyre 1991).

While fires are undoubtedly important for habitat productivity and species survival, increased fire intensity or severity may potentially put an ecosystem at risk. This is especially the case when spatial and biotic differences in vegetation are at the core of defining the extent of fire's effect on the landscape.

## 1.2. A DIVERSE HABITAT: VEGETATIVE HETEROGENEITY

Unlike other natural pressures that take decades or centuries to create any sort of significant change, fire can act on environments and wildlife on a scale of hours or minutes, resulting in widespread and immediate changes in vegetation (Pyre 1991). Fire directly impacts vegetative heterogeneity by creating extensive mosaic regimes, which can be defined as environments composed of areas with differing amounts of vegetative productivity, varying levels of fire severity, and different types of dominant vegetation all interspersed to create a dynamic assortment of land cover that is never the same as another land cover. Mosaic patterns generate several types of niches for various species to exist, thereby increasing biodiversity within a habitat (Johnsson 2011; Jeremy-Russell Smith et al. 2012).

Ultimately, fire behavior is determined by vegetation along with the spatial and temporal variation of topographical and environmental conditions that impact vegetation (Catchpole 2002). Burning is often treated more as a response to, and not always a cause of, vegetative change (Kershaw et al. 2002). Therefore, the type of vegetation and spatial layout of vegetation that composes a certain land cover is partially indicative of the potential for fire to occur and the range of fire severity and damage that can be inflicted on a habitat.

For example, an area with more understory vegetation such as tall, dry grasses is more likely to catch fire than an area with short grasses and more upper-canopy vegetation like tall wooley-butt trees (*Eucalyptus longifolia*; Fig. 1b). Invasive species, like gamba grass (*Andropogon gayanus*), can rapidly reach heights of up to 4.5m in the span of only a few years, making the potential for large fires to occur much higher for areas that have a significant amount of these types of grasses because they provide more energy than the native vegetative fuel load (Setterfield 2010).

**Figure 1b. Example of habitat heterogeneity.** Open grassland with tall grasses (*left*) vs. semi-dense eucalyptus forests (*right*)



(Photo Credit: Kelly O'Toole)



(Photo Credit: Samantha Lantz)

Vegetative heterogeneity also has many indirect effects on avian species richness and species abundance, mainly because it influences availability of invertebrate prey species (Johnsson et al. 2011; García et al. 2011). Heterogeneity is only one of many indirect influences on avian abundance, but it is an important one. It ultimately influences food availability, shelter, and cover from predators.

In summary, a range of possible habitats creates a spectrum of fire occurrence and severity throughout tropical savannas. Vegetative heterogeneity is crucial to maintaining consistent, non-threatening fire-regimes. Ultimately, changes in the mosaic patterns of an area may significantly impact avian abundance and distribution in an area.



**Figure 1c. Introduction to framework model.** The various human groups involved in fire management impact the spatial layout of vegetation, which in turn determines fire severity, while the extent of fire severity also shapes vegetative heterogeneity



### 1.3. FIRE SEVERITY

Fire severity includes many definitions, measurements, and interpretations in past studies. In this study, I refer to “fire severity” as the degree of effects that a fire may have on an ecosystem as a factor of both space and time (Keane et al. 2012), and I use differential normalized burn ratio (dNBR) as its measurement. This interpretation will remain constant throughout the study, especially because a specifically defined and constant application of fire severity is important for landscape-scale evaluations of ecological condition and vegetation communities (Keeley 2009).

It is also important to note that while fire severity and fire intensity are oftentimes used interchangeably in scientific literature, they are not synonymous terms. Fire intensity refers to the more discrete, quantifiable characteristics of fire, including vegetative fuel load and CO<sub>2</sub> emissions. In comparison, fire severity is a more qualitative measure and is more appropriate in describing the degree of change in a habitat as opposed to the actual changes that occur.

The measurement used in this study is normalized burn ratio (NBR), a satellite-derived index measuring aboveground fire severity (Keane et al. 2012). I ultimately use differential normalized burn ratio (dNBR), which measures changes in this scale over a specified amount of

time. In other words, dNBR observes the degree of change from pre- to post-fire environments (Keane et al. 2012).

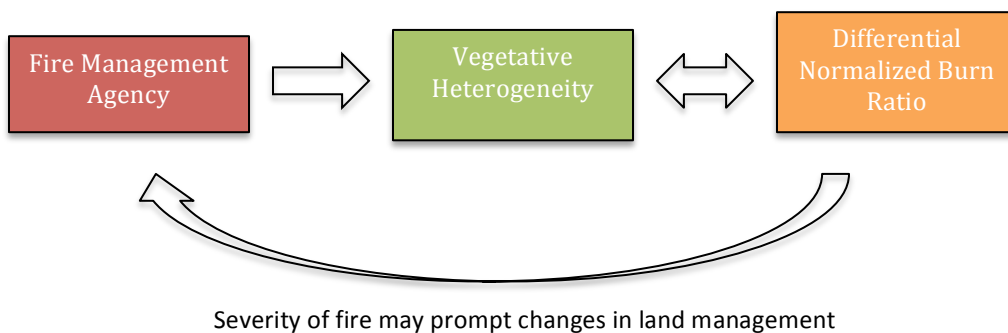
Like many other fire severity measurements, using dNBR has some limitations. One of the major problems associated with NBR imagery is upper canopy treetops getting in the way of obtaining an accurate reading (Roy et al. 2006). However, Australian tropical savanna is mostly open habitat, so there is a smaller chance of dense treetops obscuring the image. While some argue that dNBR is not very accurate, previous studies have been able to ascertain fairly accurate measurements and to confirm accuracy by comparing dNBR results to other types of measurements (Escuin et al. 2008). Additionally, many argue that analyzing dNBR by itself does not provide a robust interpretation of fire severity. Therefore, coupling dNBR with other measurements is an ideal way to analyze fire severity over a landscape. Using dNBR in conjunction with a measure of vegetative productivity known as differential normalized difference vegetation index (dNDVI) has successfully measured change caused by fires over time throughout a landscape (Escuin et al. 2008; Lutz et al. 2011). dNBR and dNDVI will be further discussed and defined in Section 2.3.2.

As previously stated, burning can be seen as both a response to and cause of vegetative heterogeneity (Fig. 1d). Depending on factors such as time before previous fire and spatial distribution, increased fire severity can decrease habitat heterogeneity, thereby creating less niches and food sources for organisms such as birds and reducing the overall abundance of vegetation that is required for an organism to survive (Murphy & Russell-Smith 2010; Clavero et al. 2011; García et al. 2011). Fire severity affects species occupancy by altering the resources available to organisms. These threats to species abundance and biodiversity along with other

pressures can prompt land managers to change how they alter vegetation in order to attempt to change fire severity (Fig. 1d).

Here I introduce a basic framework model for the interpretation of ecological and anthropogenic processes involved in fire management that are of focus in my study. The next section will continue to add onto this framework by describing how land management and anthropogenic fire can directly affect vegetative heterogeneity, thus influencing both fire severity and potentially species occupancy.

**Figure 1d. Framework model with focus on potential effects of fire severity.** Fire severity, as measured by differential normalized burn ratio (dNBR), directly influences vegetative heterogeneity and may also prompt changes in how various groups think about and manage fire



#### 1.4. FIRE MANAGEMENT PRACTICES: THEN AND NOW

Fire shaped the Australian landscape long before humans reached the continent approximately 50,000 years ago (Kohen 1995). Tropical savannas were always exposed to constant lightning-induced fires, providing an ideal environment for Australian flora and fauna to develop different adaptations to survive and even thrive in the harsh conditions created by constant and often intense fires.

When Aborigines first arrived, they soon took advantage of the fire-prone environment and the adaptations of its endemic species by using fire as a tool to shape the environment. Early aboriginal relationships with fire are evident in archaeological evidence that indicate prehistoric non-random fire patterns (Head 1994). As indigenous communities burned, they created a network of patches committed to memory, knowing in extensive detail the types of plants and animals that lived in a particular type of habitat and what was needed to maintain certain numbers of these biota throughout their regimes (Fowler 2013). Establishing a consistent fire regime and acquiring significant knowledge on the species impacted by regular anthropogenic fire were necessary to ensure human survival in this harsh, dynamic landscape. By altering the landscape, Aborigines were able to essentially farm wildlife by creating ideal conditions for prey populations to grow (Bird & Bird 2008). Indigenous communities were deeply connected to the land for their livelihoods and ecologically-rooted cultural beliefs. This connection is encapsulated in the term “Country” to describe the land as an integrated, collective system (Head 1994).

Mosaic, non-random burning continued over the next 50,000 years until the arrival of Europeans in the early seventeenth century (Kohen 1995). It was then that the environment experienced a new fire regime, or lack thereof, in the course of only a couple hundred years. Fire was fairly consistent over the Holocene period (Veth 2007), and it is without question that the greatest variation of fire regime in the Northern Territory occurred during the period of initial European occupation (Kershaw et al. 2002). This shift was mainly due to European preconceived notions and aversions towards fire management.

Australia as the “problem-child” of the British Empire was an idea commonly found among colonials (Hill 1951). English colonials drew upon the little practical experience they had and

even narrower assumptions on how to manage land from other tropical locations throughout the Empire and accepted them as part of a universal truth (Powell 1988). In the Northern Territory, this universal truth implied a complete disregard for the traditional use of fire. While indigenous individuals respected and treated fire as a means of living, Europeans viewed it mainly as a destructive force that damaged buildings and put thousands of dollars of infrastructure at risk (Powell 1988). As such, colonials typically avoided the use of fire and in many cases successfully prevented aboriginal groups from using fire to maintain their traditional regimes, as many historical accounts indicate (Preece 2002).

Ironically, these actions actually made fires *more* intense and severe due to a buildup in vegetation. It essentially acts as a large carbon sink during the dry season, providing the perfect fuel for future fires. With a lack of regular maintenance through consistent burns that the environment had adapted to over thousands of years, fire would wreak havoc on a habitat that had not been exposed to it for years. Since more intense and severe fires reduce the amount of habitat and access to food, shelter and protection from predators, the lives of many animals would be put at risk as fire severity increased (Murphy 2010).

Technology introduced by Europeans allowed easier ignition of fires in the environment. Previously, indigenous groups would set fire using a number of traditional methods, including *takulo* (striking two rocks together) and *kohe* (spinning bamboo or wood vigorously against each other) (Fowler 2013). With the introduction of lighters and matches after European settlement, the need to start a fire using traditional methods became obsolete, and the cultural meanings and ties around fire started to change drastically and in many ways become less sacrosanct (Fowler 2013). Furthermore, the continuous emigration of indigenous groups from the landscape due to

government displacement cuts their physical, and often cultural, ties with the landscape and leaves Country unmanaged and subject to destructive fires.

As fire severity and intensity increased and traditional relationships with fire and the landscape weakened, Australians, both indigenous and those of European descent, began to recognize the need to change fire management practices. These practices include the implementation of more consistent fires, burning earlier as opposed to later in the dry season when there is less fuel for fires, and recognizing the importance of slow, “cool” burns versus fast, hard-to-control “hot” burns (Russell-Smith 1997).

**Figure 1e. Cool vs. hot burns.** Slow-progressing, less damaging “cool burn” (*left*) vs. fast, intense “hot” burn (*right*)



(Photo Credit: Kelly O'Toole)



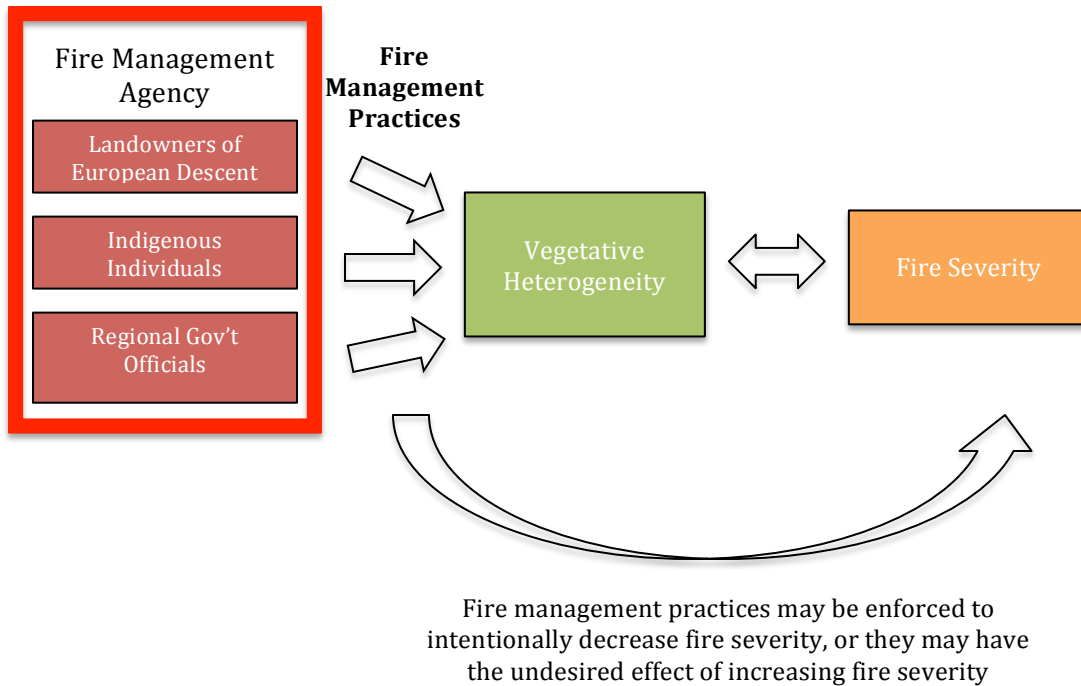
(Photo Credit: Sam Lantz)

Research and awareness about sustainable fire management picked up steam starting in the 1970s and has since continued to grow in breadth and influence throughout the Northern Territory. Much of this shift first occurred at Kakadu National Park in Jabiru, NT. The park had the first ever indigenous ranger training program, which initially served as an experiment in including traditional fire practices in park management (Lewis 1989; Russell-Smith et al. 2003).

The methods that seemed most sustainable were practices that stemmed from traditional practices and were implemented by indigenous rangers. Kakadu now serves as a model system for fire management, and many parks throughout the Northern Territory and the rest of Australia have adopted its successful techniques (Russell-Smith et al. 1997).

Currently, the use of land in Australian savannas largely involves pastoralism, defense, mining, tourism, and nature conservation (Williams et al. 2002). Savanna areas require consistent fire management, and they inevitably bring people from diverse experiences and histories together to manage the land using fire. Fire management often differs over regions based on land use and the groups managing the land. Opinions between various groups such as regional government officials, indigenous communities and landowners of European descent may vary enough to create significant differences in fire management across a habitat (Fig. 1f). These differences in opinions and actions may potentially have harmful effects on species such as the red-backed fairy-wren.

**Figure 1f. Framework model with focus on major groups involved in fire management.** Agencies of three major fire management groups are emphasized, and the practices of these groups may be enforced to intentionally decrease fire severity or they may have the undesired effect of increasing fire severity



The combined effects of fire management, vegetative heterogeneity and fire severity all inevitably impact the wildlife within a habitat. Whether this influence is positive, negative, or neutral depends on the species, the extent of each factor on the area that the species inhabits, and ultimately how these factors – especially fire management – interact with each other within a given area. It is well known that these three factors can greatly impact several avian distributions (Reside et al. 2012), and I believe the distribution of the common red-backed fairy-wren of northern tropical savannas can be similarly influenced.



### 1.5. RED-BACKED FAIRY-WRENS AND THEIR RESPONSE TO FIRE

As a common, widespread species typically found in tropical savanna habitat across the Northern Territory, red-backed fairy-wrens (RBFWs) are a good representative of the avian biota found in these environments. Being the smallest fairy wren weighing an average of 8 grams, they are little yet hardy individuals that make their home in open grasslands with grasses of medium to tall height (1.5 to 3m; Rowley & Russell 1997). It is here that they hide from predators such as the grey butcherbird (*Cracticus torquatus*) and laughing kookaburra (*Dacelo novaeguineae*), seek shelter during monsoonal rains and chilly winter nights and forage on insects such as beetles, ants, grasshoppers and cockroaches.

**Figure 1g. RBFWs and habitat distribution.** Bright RBFW male and dull individual (*left*) and habitat distribution in bright red (*right*)



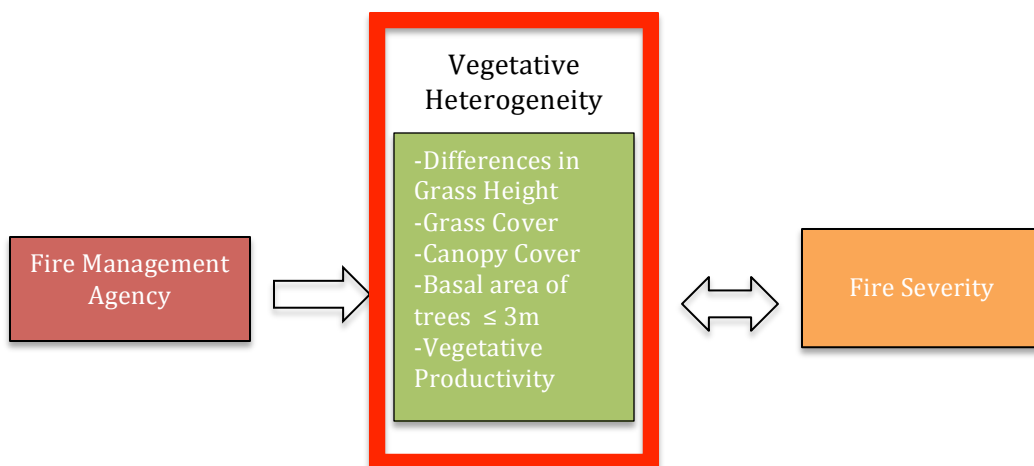
(Photo Credit: Sam Lantz)



RBFWs are generally weak flyers, requiring them to ensure that they have enough vegetation in an area to provide food and cover from predators closer to the ground. Therefore, this species tends to not venture far from cover. They forage in large, family groups for protection from predators (Rowley & Russell 1997).

Not only are RBFWs recognized as preferring unburnt to recently burnt vegetation (Rowley & Russell 1997), but studies have also demonstrated that they are negatively affected by fire (Murphy et al. 2010; Valentine et al. 2007; Nakamura et al. 2012). This may be because of their limited flying capabilities and small size, leading them to prefer niches with an abundance of vegetation. However, the specific characteristics influencing the extent of fire's impact on RBFWs has remained relatively unexplored and unknown. If RBFWs are negatively affected by fire, what aspects of fire are most influential for their welfare? And is it always the case that fire negatively affects distribution, or is this an over-generalization? I argue that the indirect effects of specific vegetative characteristics of an environment and the direct effects of fire severity on RBFWs may be adequate indicators of their welfare, and that fire may not always be a negative factor for RBFW habitat preference (Fig. 1h). Since RBFWs are territorial and tend to stay in the same area, species occupancy is used as an effective means to measure the type and magnitude of response to fire.

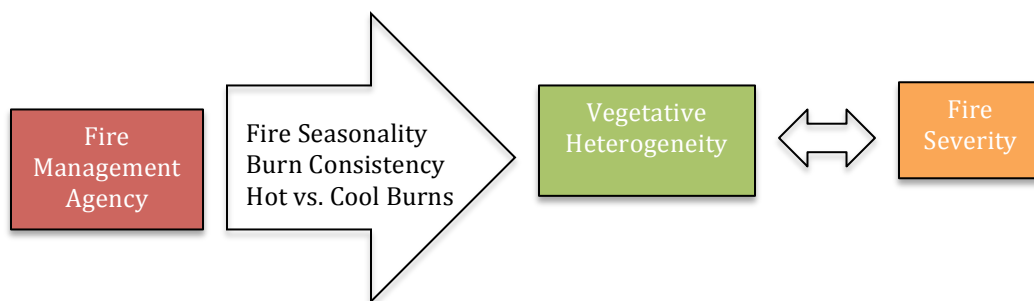
**Figure 1h. Framework model with focus on vegetative heterogeneity.** Examples of vegetative parameters that may affect RBFW habitat distribution; these changes may affect fire severity levels by increasing or decreasing the amount of fuel available for fires and the spatial extent of fire



## 1.6. RBFWS AND FIRE MANAGEMENT

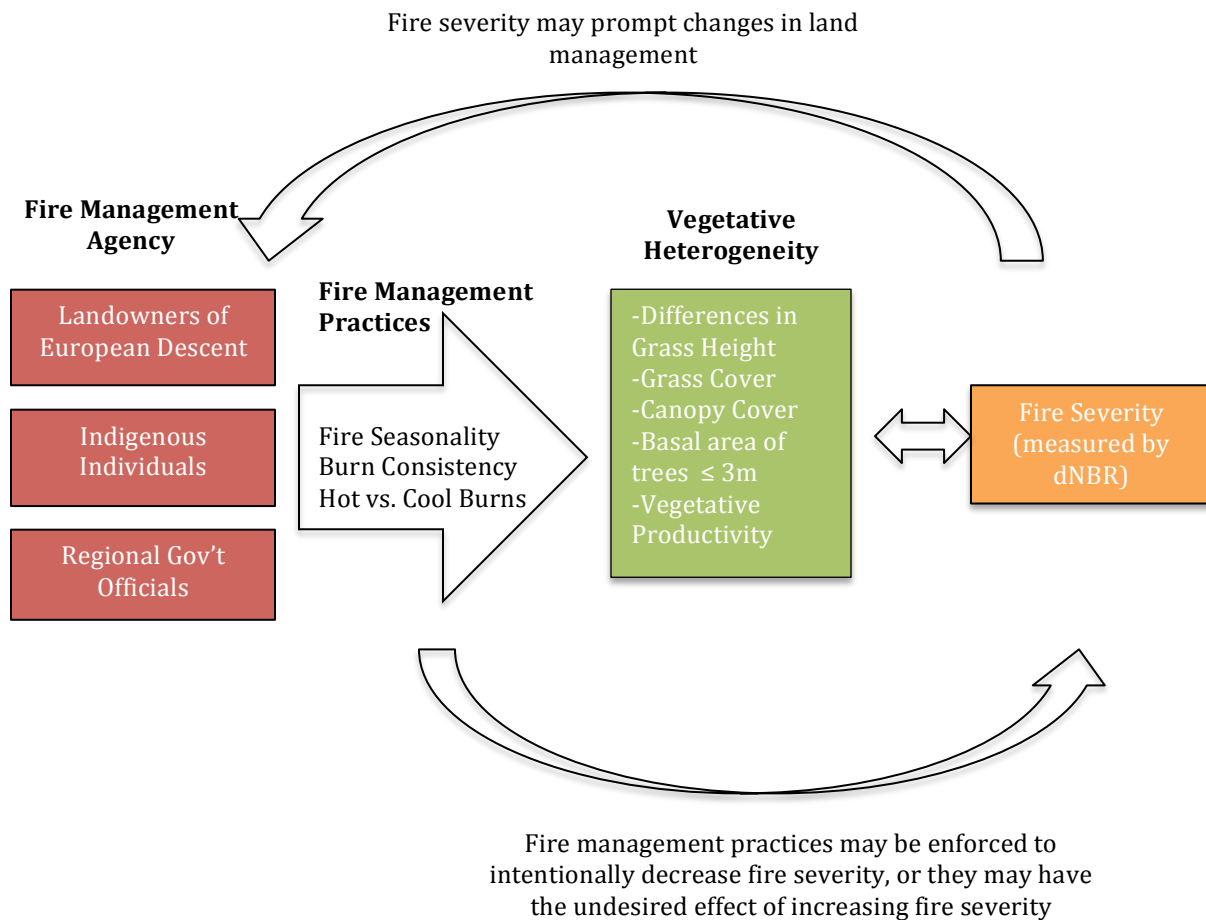
When considering the characteristics described in the previous section, it is not a stretch to deduce that changes in vegetative heterogeneity and fire severity may greatly impact the amount of ideal niches available to RBFWs individuals. These factors are largely determined by fire regimes, meaning that fire management practices undoubtedly have a large impact on the welfare of the RBFW. If these factors indeed have a large effect on the areas that RBFWs occupy, variations in fire management practices may also have implications for the types of habitats RBFWs will occupy because of their relationship with both vegetative heterogeneity and fire severity. For RBFW welfare, it may be that fire regime history, current changes in the fire regime, and predictions and recommendations for future fire management practices are all important to consider. I argue that these concerns can also be applied to other species with which RBFWs interacts. As previously mentioned, important fire regime/management factors include fire seasonality (*i.e.* early vs. late season burning), burn consistency, and the implementation of more cool burns (Fig. 1i).

**Figure 1i: Framework model with focus on effects of changes in fire management on RBFWs.**



My study measures parameters for vegetative heterogeneity and fire severity within RBFW habitat to determine if they explain RBFW occurrence. I analyze parameters deemed significant for determining occupancy and subsequently juxtapose occupancy analyses with interview evaluations of the opinions and practices of various individuals involved in fire management. A positive framework model for RBFW habitat following the format of my complete framework is introduced to summarize and organize my results (Fig. 1j). Finally, I propose future fire regime strategies and possible avenues for collaboration among groups to benefit the RBFW and other species in the NT and beyond.

**Figure 1j. Complete framework model.**



## 2. Methodology

### 2.1. BACKGROUND

#### 2.1.1. Project Information

Field data were collected under a National Science Foundation Research Experience for Undergraduates (NSF-REU, Award Number 1131614) with the intent of studying behavioral ecology of the RBFW. This three-year study encouraged students to formulate and conduct their own research projects, which involved several forms of data collection.

#### 2.1.2. Site Information

The study site was located in Coomalie Farm near the small town of Batchelor, Northern Territory, Australia (13°02' S, 131°02' E), which has been described as “a signpost on the Stuart Highway, with a pointed hand, a deserted little railway shack in the long grasses – not even a notice to whistle – only that and nothing more...” (Hill 1951, p. 275). The site is characteristic of Australian tropical savanna in which natural and especially anthropogenic burns are highly prevalent during the dry-season. A mosaic of burned and unburned patches with high vegetative diversity make it an ideal place to observe habitat heterogeneity related to fire.

### 2.2. QUANTITATIVE SAMPLING METHODS

#### 2.2.1. Transect-Based Point Count Surveys

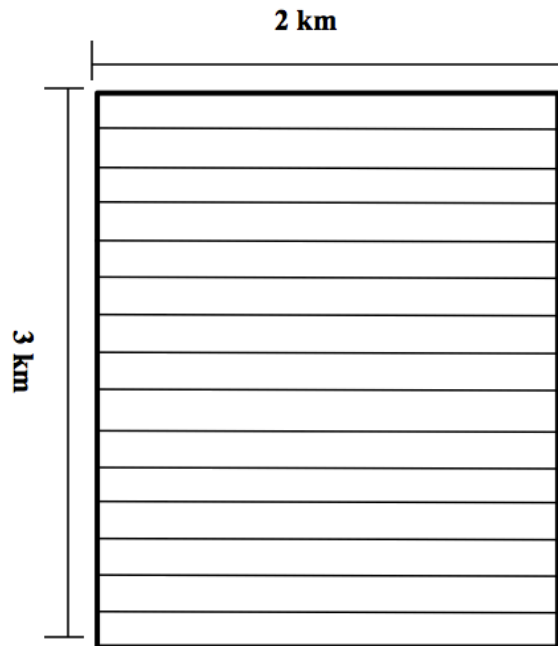
A main objective of conducting avian point counts is to systematically estimate occurrence of RBFWs within a large tract of tropical savanna habitat. Evenly-spaced horizontal transects running east-west served as a template for point count surveys. Surveys were conducted

by two undergraduate biology students with training from experienced professors and a graduate student from Tulane University with extensive field experience.

The study plot was limited to a 2 x 3km area and divided into sixteen transects spaced 200m apart. Each east-west transect is randomly assigned a number and denoted with a cardinal direction of either East or West. Transects are completed in an order based on their randomly assigned number. Using a compass, the survey conductor walks towards the direction assigned to each transect. Each transect was started at approximately 0600 to control for a bias of bird activity due to time of day. Along the transect, the conductor uses a handheld GARMIN GPS to mark every 200m traveled. This 200m distance denotes an intersection point of evenly spaced north-south transects. At each intersection along a given east-west transect the conductor performs a point count, in which the conductor stops for five minutes to listen and look for RBFW activity. If birds are seen or heard, their location is flagged and marked with a GPS point. If birds are not seen or heard, the conductor continues along the transect, stopping for another five minutes at the next intersection point. After their completion, the transects are then repeated in the same random order in a reversed direction.

All surveys are either marked as "USE" (survey of area where RBFW presence had been detected) or "non-USE" (survey of area where RBFW presence had been detected).

Researchers returned within a week of transect observations and conducted systematic vegetation surveys at the locations of previous RBFW observations, which will be discussed in more detail within Section 2.2.3.

**Figure 2a. Transect Outline for Point Count Surveys.**

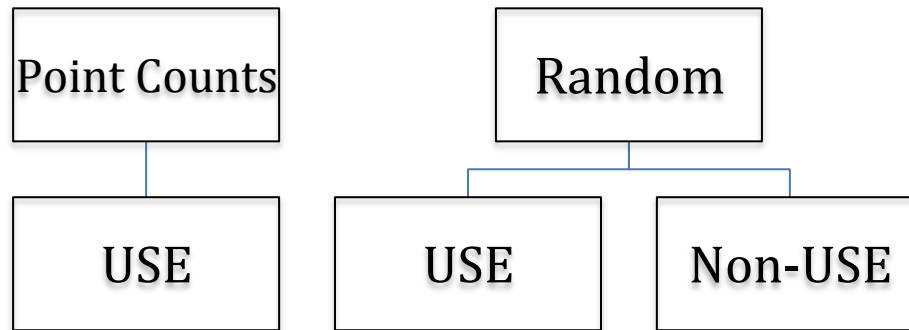
Random sampling methods of RBFWs are included in this study. Numerous vegetation surveys were used as replacements for missing vegetation data from point count observations.

For points obtained randomly, ArcMap are used to randomize GPS points and bearings within the  $2 \times 3$  km transect area. Field researchers walk to the computer-generated points and from there pace 200m in a randomly determined cardinal compass bearing (i.e.  $90^\circ$ ,  $270^\circ$ , etc.) associated with that point. If at any time RBFWs are heard or seen along the 200m walk, field researchers deviate from the random transect line and conduct a vegetation survey at the location where RBFW(s) were seen or heard. After walking 200m without observing any RBFW activity, a final two-minute observational survey is conducted to detect possible presence of RBFWs in the surrounding area. Surveys are performed in areas of detected RBFW activity if their presence was identified during the two-minute trial. As for the point counts, these surveys are included in the collection of total USE surveys. If no RBFWs are heard or seen after this trial, the end of the

200m on the specified bearing served as the location for our non-biased vegetation surveys, and they are included in our collection of total non-USE surveys. The point of observation is recorded in a GPS, and a vegetation survey is then conducted at this site at a later time.

I use this information to determine RBFW occupancy and only use random-sampled surveys to use the vegetation surveys that were produced by them.

**Figure 2b. RBFW survey possibilities.** Two Sampling Types (Point Counts and Random Sampling) and Possibility of RBFW Presence (USE) vs. Absence (NONUSE)



### 2.2.2. Vegetation Surveys

For each vegetation survey performed for transect observations, 10x10m plots are established around the area in which a RBFW was previously observed. Plots are subjectively designated as “burned” or “un-burned” based on new growth, blackened ground from past burns, density of grass cover, and evidence of fire damage on tree trunks. Typically, burned plots had short grass with a significant amount of bare ground and few saplings while unburned plots had more grasses of various heights, less bare ground, and more saplings. Within these plots, pairs of trained surveyors recorded approximate percent cover of bare ground, rocks, and grasses at 0.2m, 0.5m, 1.0m, 1.5m, 2.0m, 2.5m, and 3.0m in height. These metrics, including quantity of trees and saplings and their respective DBH, are used to describe overall vegetation character within the



specified area and organized plots into distinct categories. All surveys conducted at the location of a previous transect observation are categorized as “USE.” Vegetation surveys were not conducted at point counts where RBFWs were marked as absent. Therefore, surveys of random sites within 139m of the original transect-based point-count are used because they are likely representative of the vegetation type within the area of a point count at the time of a point-count survey. Random sampled surveys that qualify from this description represent “non-USE” points.

## **2.3. QUANTITATIVE ANALYSES OF FIELD DATA**

### 2.3.1. Determining Detection Probability, Effective Radius Surveyed, and Site and Sample Covariates

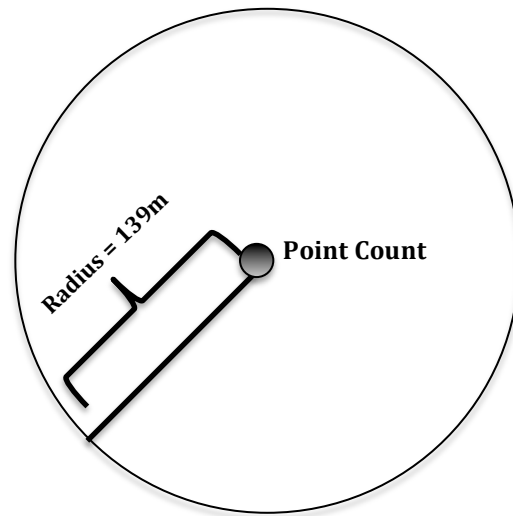
Occupancy modeling is employed to describe the sampling and site covariates that may impact RBFW occupancy. These covariates are defined and further explained in the results of my study.

It is impossible to assume that all RBFWs present in an area will be accounted for during transect surveys, especially when the distance between observer and RBFWs are essentially an estimate at the observer's discretion at the time of survey (Thomas 2010); therefore, I estimated detection probability and effective radius surveyed to determine an appropriate distance from a point count to where a RBFW was heard or seen. Detection probability is the probability that an observer will see or hear an individual or species given that it is there, while the effective radius surveyed is the distance at which an observer is as likely to miss an individual at distances shorter than the effective radius as to detect an individual at a distance farther than the effective radius (Thomas 2010). *Distance 6* (Thomas et al. 2010) was used to estimate effective radius surveyed and calculate detection probability, or  $p$ . I found that detection probability was relatively low ( $p = 0.17$ ), which is common for many avian surveys (Thomas 2010). Therefore, it

is particularly important to determine what observations should be included based on distance from point counts due to its low detection probability.

The effective radius surveyed is 139m, meaning that every observation within 139m was counted as a presence. Observations made outside of this range were omitted because of low levels of detection past that effective survey radius (Fig. 2c). The half-normal (key function) algorithm with a cosine series expression was found to be the best fit for the data. A 550m truncation was applied in order to eliminate extreme outliers.

**Figure 2c. Buffer zone for point counts and transect vegetation surveys.**



Once a 139m buffer zone was calculated, *Presence* software (Freeman & Moisen 2008) is used to determine which habitat covariates might impact RBFW occupancy. This included both plots where RBFWs are present ( $n = 32$ ) and point counts where RBFWs were absent ( $n = 74$ ). Sampling covariates varied between surveys and were used to determine whether they affected detection probability, while site covariates did not change between surveys and were ultimately used to observe whether they affected RBFW occupancy.

The following sampling covariates are used to evaluate heterogeneity in detection probability: Julian date, time of day, and high grass (2-3m high). Additionally, the following site covariates are used to evaluate heterogeneity or fire severity in occupancy: percent canopy cover, basal area of trees/woody shrubs with a diameter at breast height (DBH)  $\leq$  3m, basal area of trees/woody shrubs with a diameter at breast height (DBH)  $>$  3m, number of saplings, high grass (2-3m high), low/medium grass (0.1-1.5m high), total grass cover (see Table 2a). Vegetative productivity (dNDVI) and fire severity (dNBR) levels on a landscape scale are also included in occupancy analyses, as discussed in further detail in section 2.3.2 (see Table 2a).

The height cut-off for trees and woody shrubs is at 3m because RBFWs are documented as foraging and living predominantly at ground level or below 2m vegetation height (Rowell & Russell, 1997, 49). They are known to probe for insects in eucalyptus trees as well; therefore, trees and woody shrubs are included in my analysis.

**Table 2a. Explanation of vegetative parameters measured in *Presence*.** Sampling covariates are italicized and site covariates are bolded.

VEGETATIVE PARAMETER	EXPLANATION
<i>Julian Date</i>	Elapsed number of days since start date of first transect survey
<i>Time</i>	Time of RBFW Observation
<b>Percent Canopy Cover</b>	Amount of canopy cover estimated when using a cylindrical densitometer to look up at the canopy
<b>Basal Area of Woody Vegetation (<math>\leq 3\text{m}</math> and <math>&gt;3\text{m}</math>)</b>	Area of survey that is occupied by the cross section, or diameter at breast height (DBH), of trees or other woody vegetation
<b>Low and Medium Grass</b>	All grasses measuring between 0.1m and 1.9m
<i>Tall Grass</i>	All grasses measuring between 2m and 3m
<b>Total Grass</b>	Total amount of grass cover
<b>dNDVI</b>	Difference of Normalized Differential Vegetation Index between July 2011 and July 2012
<b>dNBR</b>	Difference of Normalized Burn Ratio between July 2011 and July 2012

### 2.3.2. Occupancy Modeling in *Presence*

All sampling and site covariates mentioned in Section 2.3.1 are included in occupancy modeling within *Presence* (Table 2a; Freeman & Moisen 2008). Occupancy modeling is largely based on the measurement and inclusion of two main parameters: detection probability ( $p$ ) and psi ( $\psi$ ). As previously stated, detection probability is the likelihood that a survey will detect an individual if it is actually present at a site (MacKenzie et al. 2006). For example, one may find five RBFWs during a survey when there are actually ten in that area. This means that  $p = 0.5$ , or a site surveyor is likely to detect half of the individuals actually present. Psi represents species occupancy, or the likelihood that an individual or species will occupy a certain area (MacKenzie 2005).

Both of these parameters may not be affected by any factors, or covariates, found in the same habitat. This describes a null model, which is a highly unlikely situation. Humans are not perfect at detecting every single individual in an area, and biological phenomena do not occur in a vacuum, therefore  $p$  and  $\psi$  are likely to be impacted by some factor. In my analysis, I employ a null model for  $p$ ,  $\psi$ , and both  $p$  and  $\psi$  to set as a model that others are compared to in order to determine if any null model describes RBFW occupancy at Coomalie Creek the best. This is visualized by a  $\psi(.)p(.)$  model, indicating by the “.” between parentheses that a model is null for both parameters.

Next, I employed models where  $\psi$  is kept null and only  $p$  is affected by covariates. This is symbolized by a  $\psi(.)p(y)$  model, where  $y$  is equal to either individual sampling covariates or a combination of covariates. A similar approach to the sampling covariate analysis is used for the site covariate analysis. Site covariates by themselves along with different combinations of covariates were modeled and compared to the constant- $p$  model. Represented by  $\psi(x)p(y)$ , this model is used to observe what site covariates  $x$ , if any, significantly altered  $\psi$ , or where RBFWs are found in the study site, while incorporating any sampling covariates that are found to influence  $p$ . All  $\psi(x)p(y)$  models that best explained RBFW occupancy were averaged with a 0.95 confidence interval.

It is important to note the possibility that  $x$  and/or  $y$  may remain null depending on their comparative fits. To determine which models explained RBFW occupancy the best, I employed Akaike's Information Criteria (AIC<sub>c</sub>) to conclude which models best estimate the “true” process explaining RBFW occupancy (Symonds and Moussalli 2011). The lower the AIC<sub>c</sub> value, the closer a model is to explaining why RBFWs occupy a certain area.

### 2.3.3. GIS Analysis for Fire Severity

I retrieved MODIS (Moderate Resolution Imaging Spectroradiometer) 250m resolution satellite imagery of this area from the North Australian Fire Information (NAFI) database. Both mean Normalized Difference Vegetation Index (NDVI) and mean Normalized Burn Ratio (NBR) are calculated for multiple scenes, or large geographic areas represented in GIS, for each 250×250m block within the transect area by utilizing *ArcGIS 10* software (ESRI 2011). NDVI measures green vegetative productivity by analyzing near-infrared (NIR) and visible (VIS) bands, while NBR measures fire severity by evaluating near-infrared and mid-infrared bands (MIR). NIR and VIS depict changes in vegetative productivity or plant damage that may or may not be caused by fire. MIR reflectance increases immediately after fire according to how severe a fire was in a particular area, thereby providing a good estimate of the extent of fire severity between pixels (Epting 2004).

$$1. \text{NDVI} = \frac{(\text{NIR} - \text{VIS})}{(\text{NIR} + \text{VIS})}$$

$$2. \text{NBR} = \frac{(\text{NIR} - \text{MIR})}{(\text{NIR} + \text{MIR})}$$

In order to assess the major temporal aspect of fire severity and its possible effect on RBFW, difference between NBR (dNBR) data were calculated between pre-fire and post-fire values between 2011 and 2012. This ratio was also calculated for vegetative productivity during the same years using NDVI. Both were calculated via GIS models using the following formulas:

$$3. \text{dNBR} = \text{NBR}_{pre} - \text{NBR}_{post}$$

$$4. \text{dNDVI} = \text{NDVI}_{pre} - \text{NDVI}_{post}$$

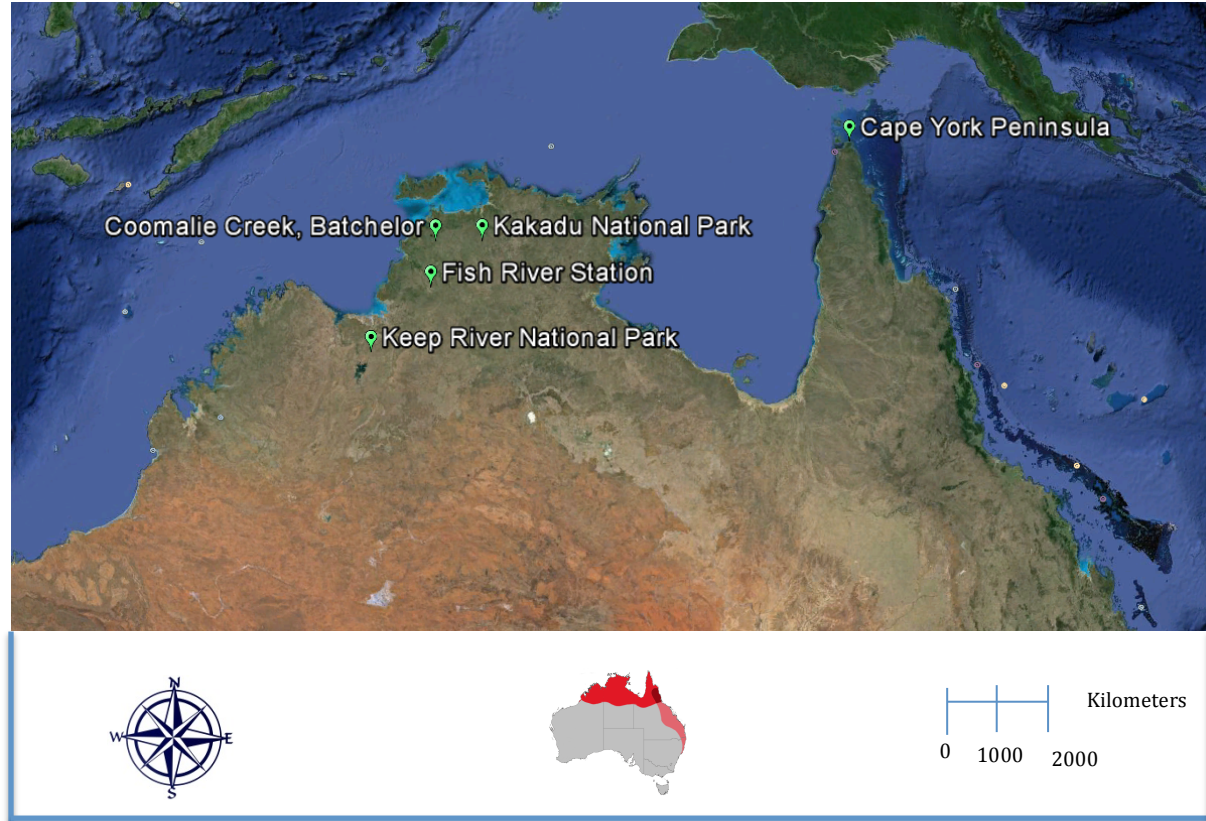
## 2.4. QUALITATIVE ANALYSES OF FIRE MANAGEMENT PRACTICES

Semi-structured ethnographic interviews were employed for seven individuals throughout RBFW territory (Fig. 2d). The first goal of these interviews is to better understand how different groups and individuals use fire to manage land and how they view their interactions with ecosystems and other people involved in fire management. The second goal is to apply interview responses to RBFWs and compare interview responses with RBFW occupancy results.

Individuals were not randomly selected. Participants were selected based on their association with one of three groups, or roles in fire management: regional government official ( $n = 4$ ), landowner of European heritage ( $n = 2$ ), and indigenous or traditional landowner ( $n = 2$ ). Due to the multiple identities to which one individual associated him or her self, he/she is counted as a landowner of European heritage and a traditional landowner.

Individuals were also selected according to their geographic location. Most importantly, all must be in areas where RBFWs are found throughout the landscape. I attempted to have a concentration of participants in Batchelor ( $n = 3$ ) to represent the study site. I also made an effort to interview representatives from other parts of the RBFW's natural range, including one participant from Queensland and another close to Western Australia.

**Figure 2d. Locations of participants' current or previous application of fire management.**



All questions were somehow related to fire, fire management, species response to fire, their role in fire management, and their opinions on fire management and how others conduct it (see Appendix 6.1). Questions were planned before interviews took place, but they varied in order and according to whom I was asking. Some were only different in the groups they were addressing within the question, while others were unique to that group.

Questions mainly differed to accommodate the three groups described previously. For example, I would ask the question “How long have you owned your property in Batchelor, NT?” to a landowner of European heritage, but I would ask “How long have you worked at x park?” to a regional government official. While both sound the same, both can mean very different things for either individual. The landowner might describe how he acquired his or her land and what



this meant for his neighbors, while the government official could mention the parks he or she worked in before and how that person's beliefs changed between jobs. However, I ensured that I asked questions that would evoke responses that touched upon the same topics so that I could compare interview responses in a thematic analysis.

My study employs a thematic analysis to focus on major themes that are present throughout all interviews. First, interviews were coded. Codes are defined as any words, phrases, or ideas that could be clearly identified in at least one interview and that had the potential to be applied to other interviews (Creswell 2013). Initially, coding was used to focus on micro-themes and collect these smaller codes into larger "umbrella" themes that could describe similar or differing patterns of thought concerning fire management between different fire management groups and individuals (Creswell 2013). Codes were associated to particular themes, not specific questions.

In the second stage of analysis, these themes were juxtaposed against current literature in a comparative analysis that reflects upon the similarities and differences between individuals involved in fire management within RBFW habitat, the opinions of individuals with similar fire management roles, and the latest scientific research models that suggest consistent and non-random, low-intensity mosaic burning.

All interviews are conducted within three months of each other during the wet season, when fires are not as common. Therefore, differences in current conditions should not be a factor affecting responses, and participants are more likely to consider entire seasons in their responses as opposed to a specific large fire or lack of fires that may have otherwise taken place during the time of the interviews.

I conducted all interviews over the phone using Skype<sup>TM</sup> Internet calling along with an online recorder and handheld recorder to document discussion with participants. Only my advisor, Dr. John Swaddle and I are privy to participant information and recorded/transcribed interviews.

The identities of these individuals remain confidential throughout my research, however their associated institutions and locations are identified with participant permission. The interview protocol complied with appropriate ethical standards and is exempted from the need for formal review by the College of William & Mary Protection of Human Subjects Committee.

### 3. Results

#### 3.1. OCCUPANCY MODELING

##### 3.1.1. Occupancy Modeling of Sampling Covariates [ $\psi(\cdot)p(\gamma)$ ]

All possible combinations of sampling covariates (*e.g.* Julian date, time, and tall grass) are modeled and compared to a “constant- $p$ ”  $\psi(\cdot)p(\cdot)$  model, which assumes that species at all sites and surveys are detected equally. Data were also compared to a “survey-specific  $p$ ”  $\psi(\cdot)p(\cdot)$  model, assuming that detection probability is not the same between surveys. I ran both models in order to determine if detection probability varied between surveys. The  $AIC_c$  value for the constant- $p$  model was lower than the value for the survey-specific  $p$  model. Therefore,  $p$  is best explained when  $p$  is constant between surveys.

When comparing sampling covariates and all combinations of sampling covariates that might improve a model, no models were found to produce  $AIC_c$  values lower than the constant- $p$  model (Table 6.2.2.). None of the sampling covariates significantly lower detection probability. Therefore, all models that incorporate site covariates as factors that may influence  $\psi$  are compared to the  $AIC_c$  value of the constant- $p$  model. Since the null model worked best for  $p$ , a  $\psi(x)p(\cdot)$  model is employed.

The null, constant- $p$  model yields a low detection probability ( $p = 0.18 \pm 0.09$ ). While this may seem problematic, detection probabilities this low are typical in occupancy studies on avian species (Dr. Matthias Leu, personal communication).

Due to the small amount of replicate surveys ( $n = 2$ ) to each point count location, sampling covariates may actually show an impact if more than two surveys are conducted. However, there are none that are significant enough to show any influence between the two

recorded visits. While this limitation in determining variables that may influence detection probability exists, I assume that none are influential enough to have a large effect on the occupancy analysis.

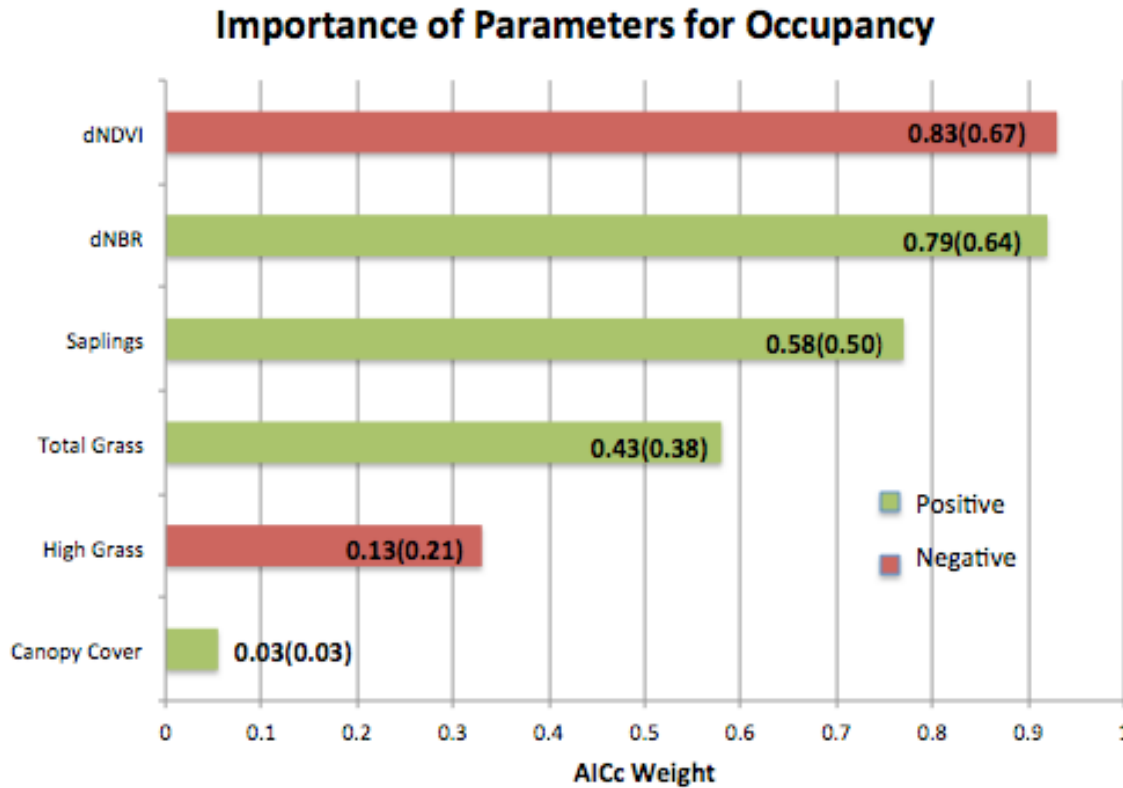
### 3.1.2. Occupancy Modeling of Site Covariates [ $\psi(x)p(y)$ ]

There are ten models that produce lower  $AIC_c$  values than the  $\psi(.)p(.)$ . The site covariates that are incorporated into at least one of these models include dNDVI, dNBR, total grass, high grass, saplings, and canopy cover. To understand the importance of these variables in RBFW occupancy, or to find the most explanatory variables, covariates are weighted and averaged across models (Table 6.2.3.).

Current literature regarding occupancy modeling stresses that models within 4  $\Delta AIC$  of the model to which it is being compared is considered equivalent (Burnham and Anderson 2002). Only the top two models are greater than 4  $\Delta AIC$ ; therefore, only these two models are considered as being of best fit and describing occupancy. These include both  $\psi(\text{total grass} + \text{saplings} + \text{dNDVI} + \text{dNBR})p(.)$  and the  $\psi(\text{total grass} + \text{saplings} + \text{dNDVI} + \text{dNBR} + \text{high grass})p(.)$  models.

The  $AIC_c$  values for the site covariates included in these models (*e.g.* total grass, saplings, dNDVI, dNBR, and high grass) along with their respective slope and SE are weighted and compared (Fig. 3a)

**Figure 3a. Occupancy modeling results.** Average weighted  $AIC_c$  values by parameter are plotted for each covariate used to model heterogeneity in occupancy. Values in bar graph represent slope estimates (SE) for each covariate.



The covariates with the greatest importance for determining RBFW occupancy are dNDVI ( $AIC_c$  weight = 0.93) and dNBR ( $AIC_c$  weight = 0.92). Their respective relationships with occupancy suggest that RBFWs are more likely found in areas experiencing a recent reduction in vegetative productivity and increase in fire severity, or in other words, areas experiencing recent intense burns. This is also supported by the positive relationship found between RBFW occupancy and saplings: areas that have been recently burnt will tend to have more regrowth because of higher nutrient availability in the burnt soil (Johnsson 2011). However, RBFWs still tend to occupy areas with more grass cover, which is a less important relationship than dNDVI, dNBR and saplings. The SE of high grass and canopy cover strongly

overlap with zero, so they do not have a reliable relationship with RBFW occupancy. Therefore, these relationships are unknown.

### 3.2. INTERVIEW ANALYSIS

#### 3.2.1. Roles of Interview Participants

While the names of participants are not revealed, their general role in fire management is emphasized in this analysis. Participants #1-4 currently or previously worked as park rangers, overseers of parks, or consultants of parks in the Northern Territory. Participant #5 is a landowner of European descent in Batchelor. Participants #6-7 either ethnically identify as indigenous or affiliate themselves with them. Participant #7 is a pastoralist and cattle-farm owner in Batchelor whose mother was a traditional indigenous tribeswoman and whose father was a landowner of European descent. However, Participant #7 identifies almost exclusively with his/her indigenous roots.

**Table 3d. Roles of participants.**

	Role of Participant
Participants #1	Used to work with multiple parks throughout the Northern Territory, now involved in academic research on fire management
Participant #2	Manages land that is collaboratively handled by indigenous land owners, the Nature Conservancy, the Australian federal government, etc.
Participant #3	Park ranger for many parks around the Batchelor area
Participant #4	Consultant for Kakadu National Park who including indigenous individuals as rangers for their important ecological knowledge on fire and tropical savanna habitats; now works as an environmental educator
Participant #5	Landowner of European descent in Batchelor

Participant #6	Focuses on indigenous studies, has extensive experience with avian field work in the Northern Territory
Participant #7	Indigenous pastoralist and cattle-farm owner in the Batchelor area

### 3.2.2. Themes and Codes

After transcribing interviews, I compiled a list of codes that described an idea or concept related to fire management in at least one individual's response. Without relying on past knowledge and focusing solely on how code related to one another on their own, I organized them into six major themes (Table 3e): 1) Knowledge of fire and fire management; 2) "Country," 3) Negatively-viewed fire management practices, 4) Positively-viewed fire management practices, 5) Effect of anthropogenic fire on floral and faunal wildlife, and 6) Goals of fire management. All themes are composed of codes that are based on the participants' point of view, not how the interviewer may have interpreted something. However, this does not mean that interviewer bias had no effect on qualitative interpretation. Unfortunately, bias must be recognized as an inevitable limitation to interpreting results. However, this limitation was partly combated by my lack of set hypotheses to steer interpretations.

**Table 3e. Themes and their associated codes.**

<p><b>Theme #1: Knowledge of fire and fire management</b></p>	<p>1.1 Lack of fire knowledge 1.2 Retrospect on fire management 1.3 Lack of proper measurements for impacts of fire 1.4 Spreading common fire management knowledge 1.5 Shift in fire management knowledge and application 1.6 Competence in fire management 1.7 Consulting with indigenous individuals/groups 1.8 Fire plans and mapping 1.9 Lack of communication 1.10 Unequal access to knowledge</p>
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<p><b>Theme #2: Relationship with “Country”</b></p>	<p>2.1 Young vs. old generations 2.2 Absence of people in landscape 2.3 Traditional fire management 2.4 Burning for cultural reasons 2.5 Pastoralism 2.6 Referring to “Country” 2.7 Humans adapting to country 2.8 Indigenous rangers 2.9 Disruption of aboriginal regime 2.10 Farming</p>
<p><b>Theme #3: Negatively- viewed fire management practices</b></p>	<p>3.1 Helicopters and incendiaries 3.2 Throwing matches 3.3 Reluctance to use fire 3.4 Grating 3.5 Fire management administration 3.6 Burning late in season 3.7 Burning constantly 3.8 Roadside burning 3.9 European influence</p>
<p><b>Theme #4: Positively- viewed fire management practices</b></p>	<p>4.1 Cool burns 4.2 Kakadu National Park as a model system 4.3 Fire breaks 4.4 Fire management administration (i.e. CISRO, Bushfires Council) 4.5 Burn early in dry season 4.6 Small patch size 4.7 Collaboration between groups 4.8 Avoiding certain areas of habitat</p>
<p><b>Theme #5: Effect of anthropogenic fire on floral and faunal wildlife</b></p>	<p>5.1 Change in species abundance 5.2 Change in species biodiversity 5.3 Invasive vegetative species 5.4 Gouldian finches 5.6 Habitat heterogeneity 5.7 Reducing vegetative biomass 5.8 No change in species abundance or diversity 5.9 Fire as a negative impact on species 5.10 Small mammals 5.11 Fire as a positive impact on species</p>
<p><b>Theme #6: Goals of fire management</b></p>	<p>6.1 Influencing climate change 6.2 Habitat heterogeneity 6.3 Protecting human life and infrastructure 6.4 Biodiversity 6.5 Managing large areas to prevent future intense fires 6.6 Government funding 6.7 Cultural reasons 6.8 Farming 6.9 Good grass feed for cattle</p>



Next, codes are listed by theme for each participant (Table 3f). Codes are compared across participants to analyze similarities and differences between participants as individuals and as representatives of the three main fire management groups of interest. Codes are then compared qualitatively between groups.

**Table 3f. Participant codes.**

	Participant #1	Participant #2	Participant #3	Participant #4	Participant #5
Knowledge of fire and fire management	1.1, 1.2, 1.3, 1.4, 1.5, 1.7, 1.8, 1.9, 1.10	1.3, 1.5, 1.7, 1.8	1.7, 1.8	1.1, 1.4, 1.5, 1.7	1.5, 1.8
Relationship with "Country"	2.1, 2.3, 2.5, 2.6, 2.7	2.2, 2.3, 2.8	2.3, 2.8	2.3, 2.6, 2.7, 2.8, 2.9	2.2, 2.3, 2.5, 2.7, 2.10
Negatively-viewed practices	3.1, 3.2, 3.3, 3.4, 3.6, 3.7, 3.8	3.4, 3.6, 3.9	3.1	3.1, 3.3, 3.7	3.1, 3.2, 3.3, 3.4
Positively-viewed practices	4.3, 4.4, 4.5	4.1, 4.3, 4.5, 4.6	4.4, 4.5, 4.6, 4.7, 4.8	4.1, 4.2, 4.4, 4.7	4.1, 4.3, 4.4, 4.6
Effects of fire on floral and faunal wildlife	5.1, 5.2, 5.3, 5.7, 5.8, 5.9	5.1, 5.6, 5.10	5.1, 5.2, 5.3, 5.6, 5.7, 5.8	5.5, 5.6	5.3, 5.4, 5.6, 5.7
Goals of fire management	6.1, 6.2, 6.3, 6.5, 6.6, 6.7	6.1, 6.2, 6.4, 6.5, 6.7	6.2, 6.4, 6.5	6.3, 6.4, 6.5	6.3, 6.5

Participant #6	Participant #7
1.4, 1.5, 1.7, 1.9	1.6
2.3, 2.5	2.1, 2.3, 2.5, 2.6, 2.10
3.1, 3.2, 3.6, 3.7	3.1, 3.4, 3.6
4.1, 4.2, 4.4, 4.7	4.5, 4.8
5.1, 5.4, 5.6, 5.7, 5.9, 5.10	5.1, 5.2, 5.3, 5.6, 5.7, 5.8
6.2	6.8, 6.9

### 3.2.3. Patterns

Based on relative frequency across groups, several codes are shared among interview participants. No codes seemed to be particularly associated with one group over another. A small sampling size is limiting in my analysis of differential frequencies between groups. Similarly, individual agency could not be assessed due to small samples size. Therefore, patterns are focused on a core model that involves codes with the highest frequency across all individuals. They attempt to explain a more universal approach to managing fire while assessing how opinions compare and contrast between individuals. The codes that are included in this core model are summarized in Table 3g.

**Table 3g. Themes and their associated highest frequency codes across participants.**

<b>Theme</b>	<b>High Frequency Codes Across Participants</b>
1. Knowledge of fire and fire management	Shifts in fire management, consulting with aboriginal groups, mapping/planning, lack of fire management knowledge
2. Relationship with "Country"	Traditional management, pastoralism
3. Negatively-viewed fire management practices	Helicopters & incendiaries, burning late in the dry season
4. Positively-viewed fire management practices	Fire management administration, cool burns, burn early in dry season
5. Effect of anthropogenic fire on floral and faunal wildlife	Change in species abundance, reducing vegetative biomass, invasive vegetative species, habitat heterogeneity
6. Goal of fire management	Managing large areas, habitat heterogeneity

## 4. Discussion

### 4.1. MAIN FINDINGS

Despite the current literature on red-backed fairy-wrens and their response to fire, RBFWs tend to occupy environments that may reflect more heterogeneous environments with a mixture of densely vegetated patches and recent severely burned patches. While many individuals involved in fire management already emphasize practices benefiting RBFWs such as heterogeneity and collaboration, many focus on producing less intense fires through their practices, which could be detrimental to the RBFW if they indeed prefer areas that include severely burned areas. I argue that individuals across the fire management spectrum should focus on gaining awareness of site-specific species response for several species and spreading this knowledge in order for these practices to be consistent and effective throughout tropical savanna landscapes to benefit species like the RBFW.

### 4.2. THE IMPORTANCE OF TRADITIONAL FIRE REGIMES AND VEGETATIVE HETEROGENEITY

Through occupancy modeling I showed that RBFWs are more likely to be observed in areas with recent intense fires (dNBR) and a decrease in vegetative productivity (dNDVI), compared with other surrounding habitats. As fire severity increases, it is reasonable to assume that vegetative productivity will in turn decrease. It is apparent that RBFWs prefer habitats that are characterized by these relationships. Similarly, a positive relationship with saplings and RBFW occupancy is consistent with these patterns as recently burned areas will show relatively more regrowth as nutrients in the soil are uncovered by fires.

While the relationships with dNDVI and dNBR are more straightforward, the negative relationship between occupancy and total grass cover is somewhat ambiguous. How can RBFWs prefer habitat with more grass, but less vegetative productivity? If one considers the possibility of these two occurring at different locations on the same site, then this relationship becomes more intuitive. Having a vegetatively heterogeneous environment with patches of high grass yields and patches with recent burns supports this argument. It is important to note that because patchiness was not directly assessed, I cannot nor will not make any direct assumptions on heterogeneity. However, the environment at least likely demonstrates heterogeneous-like conditions.

Most previous literature on the RBFW focuses on simply tall grasses as the major substrate necessary for RBFW survival (Rowley and Russell 1991). Additionally, all known studies of RBFWs that evaluate response to fire report that RBFWs are overwhelmingly negatively affected by fire (Murphy et al. 2010). These two perspectives clearly do not match what was found in my study. I argue that this may be indicative of one of two things. A smaller sample size on a single site could produce biased and purely site-specific results that cannot be used to explain RBFW response elsewhere. On the other hand, my results could indicate a misinterpretation of RBFW habitat preference. I also argue that the later seems to be the stronger argument.

It is unclear whether heterogeneous environments are crucial for the survival of RBFWs; however, it is appropriate to correlate RBFW presence with areas that have experienced recent severe burns and to extrapolate that RBFWs have an overwhelming habitat preference for these areas. Environments where the two habitats coexist in natural or anthropogenic juxtaposition include mosaic heterogeneous environments that experience consistent, patchy burns.

Natural and anthropogenic vegetative heterogeneity were mentioned at least in some respect in every interview as either an effect of anthropogenic fire, a goal of fire management, or both. Viewing vegetative heterogeneity as an anthropogenic goal of fire implies that it is considered an important and necessary aspect of managing the landscape. Heterogeneity is often associated with biodiversity and abundance of species, which places importance on the welfare of species. While there are characteristics that individuals in fire management are aiming to apply consistently throughout an entire area such as small patch sizes and a reduction in vegetative biomass and invasive species, they are also simultaneously aiming for more varied, mosaic environments in general. There are many reasons for attempting to maintain vegetative heterogeneity, and no interviewees shared the goal of protecting species or biodiversity. Some participants focused on preventing future large fires from occurring to prevent destruction of life or property, while the reduction of anthropogenic fire's impact on climate change was another focus. No matter what the ultimate goals are behind creating a heterogeneous environment, it still may positively impact many species such as the RBFW, as my results demonstrate.

However, interview results also indicate that most individuals advocated for practices and regimes that would produce less severe burns. When comparing this to my occupancy results, it seems that the current trend in fire management may in fact be detrimental to RBFW welfare.

Patterns of participant responses support two goals: reverting back to a traditional fire regime and including indigenous individuals directly in fire management. These goals are related to and key for establishing a mosaic, patchy environment. As a previous government-employed park ranger emphasized in his interview, patchiness for patchiness' sake is not the ultimate answer; one needs to follow traditional aboriginal regimes in order to enforce the best fire management practices possible for an area. Furthermore, one cannot achieve a non-random,

traditional fire regime without simultaneously creating a patchy environment that is characterized by spatial variation and high species biodiversity (Yibarbuk 2001). By having indigenous individuals serve as park rangers and on executive boards that make decisions on joint-managed land, it is more feasible to achieve a fire regime that closely matches traditional boundaries.

As mentioned in the introduction, the focus of reverting to a more traditional fire regime began in the 1970s with the establishment of Kakadu National Park as the first park joint-managed by both indigenous rangers and rangers of European descent (Lewis 1989). During this time period, park rangers ceased to reduce or completely avoid fire and instead adapted a more consistent, selective fire regime. Almost every participant emphasized a shift in fire management of some sort that aims for regimes that mimic or are similar to traditional regimes. The idea of Kakadu is prominent in many interviews as a core model for ideal fire management practices that are still being carried out today. Ultimately, Kakadu serves as a symbol of change and collaboration in the world of fire management. However, the cool, less severe fires that fire managers strive for in Kakadu may not be the most beneficial for RBFWs and possibly other species as well. But it is possible that RBFWs benefits more from a heterogeneous environment than from having severe burns in an area.

The goals of fire management and the type of landscape that is produced from reaching towards these goals may be similar, but the outlook towards how these practices will affect the future of the tropical savanna varies between individuals (Table 4a). Some are very optimistic, insisting that the land is currently being managed in a way that very closely or identically follows traditional regimes. This idea was expressed by the participant who identified as an indigenous pastoralist and by one of the government-employed park rangers interviewed. Others such as the

indigenous consultant in Kakadu believed that an authentic traditional fire regime could never be achieved.

**Table 4a. Examples of differences in outlook on the future of fire management.**

Examples of Differences in Outlook on the Future of Fire Management
<p>“...it seems to be <b>fine the way it is</b> now, we take care of our Country”</p> <p>(Participant #7, indigenous pastoralist)</p>
<p>“...we’re still a long way from obtaining good ecological burning in this country, I think. And we’ll <b>never</b> be able to reestablish a regime like the aboriginals had”</p> <p>(Participant #4, Kakadu National Park consultant)</p>
<p>“I think from the government’s point of view, they would probably be dragged into responsibility...and would make <b>knee-jerk reactions</b>”</p> <p>“Severity has <b>changed for the better</b> in that there is less damage”</p> <p>(Participant #5, landowner of European heritage)</p>

Whether or not a truly traditional regime can ever be established ultimately is not the real concern in fire management practices and regimes mentioned within interviews. However, all individuals interviewed consider collaboration and good relations between any combination of park rangers, landowners and indigenous individuals as needed to achieve a more heterogeneous, species-diverse habitat.



#### **4.3. DIFFERENCES IN OPINION CONCERNING RBFW ABUNDANCE**

Just as individuals have different opinions on the outlook of future fire management practices, their opinions also varied on RBFW welfare in relation to fire and the current state of tropical savannas. Two individuals were completely convinced that RBFWs were drastically declining largely in part of the species' aversion to fire and due to poor fire management practices. One individual argued that RBFW abundance remained the same. The other four individuals either had no idea or stated that they were actually thriving.

Different responses on RBFW abundance and welfare can be attributed to several possibilities. RBFWs may in fact be declining in one area and thriving in another. When compared to the locations of focus for participants, this regional explanation seems to match the distribution of responses. Both individuals in Batchelor stated that RBFW populations are stable or thriving, while those in other locations stated that RBFW populations may be either stable or declining.

Another likely explanation is variation in the consistency of fire management practices and the amount of time that a habitat had to adapt to current fire regimes. While Batchelor is apparently "a very difficult place to manage fire with the amount of people that go through there" according to one previous park ranger who was interviewed, the two land managers interviewed from Batchelor seem to do well with maintaining endemic species abundance and biodiversity.

One participant is the owner of the property on which the point count surveys were conducted. He purchased the property in 1977 and continues to own and manage the land after 37 years, maintaining similar land management practices during the entire time. Approximately one-third of his land is aboriginal freehold land and has been since Europeans first established

Batchelor, meaning that traditional fire regimes have been preserved. Fire practices and regimes remain consistent and monitored throughout the property, allowing species populations time to adapt and stabilize over time. In other participant locations, the land recently underwent stricter and more regular fire regimes or lacks a strong regime with regular practices.

According to one individual who previously worked in Kakadu National Park, RBFW abundance is declining despite Kakadu being a model park for joint-management and consistent fire regimes. Kakadu may be an exception to the consistency-based explanation because of its large size. Consisting of 20,000 square kilometers, it is often a challenge to manage such a large area with a consistent regime (Lewis 1989). It is even more difficult when fire cannot be controlled on private lands that border the park, therefore making the decisions and practices of those outside the land one manages just as important as the ones they make and follow themselves. This idea will be discussed in Sections 4.4 and 4.5.

In order to preserve the types of habitat preferred and needed to maintain RBFW populations, there are certain practices that should be embraced or avoided which are emphasized by the interview analyses in my study. These practices are described in detail within the following section.

#### **4.4. BENEFICIAL AND HARMFUL PRACTICES FOR RBFW HABITAT DISTRIBUTION AND ABUNDANCE**

There are several practices that are of focus across most or all participants (Table 3g). When considering the interpretation of my occupancy modeling results, there are many practices that may increase or reduce available RBFW-preferred habitat.

Practices that are believed to increase or preserve habitat include cool burns burning early in the dry season to prevent more intense burns in the future, creating fire maps and prescribed burn plans, and consulting with indigenous groups. All of these practices together ensure the presence of both burned and unburned areas in a habitat, consistent fires that closely follow traditional regimes, and a reduction in more intense fires. Additionally, fire management administrations (*i.e.* Bushfires Council) as another positive influence on prescribed burns allow for these practices to occur regularly on a broad, landscape scale. Ultimately, all of these factors encourage environments with vegetation that varies spatially and is very diverse.

On the other hand, there are several factors frequently described throughout the interviews that may negatively impact RBFW-preferred habitat. These include burning late in the dry season, using helicopters and incendiaries to set fires, and allowing invasive vegetative species such as gamba grass and *Sorghum* grasses to propagate throughout the landscape.

However, when comparing the qualitative results to the occupancy modeling, it appears that the current focus for most fire managers may not always be the best for the overall welfare of the RBFW. Striving for less severe, less intense burns may be beneficial for RBFWs in that they promote more heterogeneity, but they also may harm RBFWs because they seem to prefer areas with recent severe burns as well.

For example, burning late in the dry season creates more intense and extensive fires that destroy most of the habitat and leaves less area for habitats of high vegetative productivity. However, it could produce more areas of severe burns, which could increase RBFW productivity.

While the use of helicopters and incendiaries is mostly viewed as a highly destructive practice, two individuals not only accepted these practices, but also used them on their own land.

If done by a well-trained individual early in the dry season, dropping incendiaries is not as destructive and threats are minimized (Yibarbuk 2001). However, this method of burning increases chances of an area being burned that usually is not burned in natural or traditional regimes. Many of these areas are refuge habitats when an intense fire comes through for species like the RBFW, so local wildlife is disadvantaged when these areas are completely burned. Therefore, the potential benefits for the RBFW in these practices may be overshadowed by its often incorrect and overly consistent use.

Invasive vegetative species are a huge issue in tropical savanna habitats, and this problem became especially evident in the past few years. Almost all participants mentioned the presence of invasive grass species within their properties. During my study, I noticed that gamba grass occupied much of the site, growing to a towering 4.5 meters in height. According to the landowner of the study site, he constantly battles with gamba grass and actively tries to reduce it on his property. He states that gamba creates five times the fuel load in the under canopy, and that has produced very large, intense fires. Since gamba grass is extremely successful in tropical savanna habitats and is fast growing, it is often very difficult to control (Setterfield 2010). Invasive species not only diminish vegetative heterogeneity, but they also produce burns so severe that they can demolish an entire habitat. At this point, severe burns are of no benefit to the RBFW.

While RBFWs may seem stable in Batchelor due to consistent, long-term fire regimes with an emphasis on many positive practices that directly or indirectly produce vegetative heterogeneity, there is still the potential for overly intense or severe burns to occur, especially late in the dry season and when more invasive grasses are present. This possibility further increases when considering the opinions and actions of those around the properties of the

participants interviewed and the lack of fire management knowledge that many, including landowners, have within tropical savanna habitats.

#### **4.5. COMMUNICATION AND COLLABORATION AS EFFECTIVE MEANS TO MAINTAIN SPECIES ABUNDANCE AND BIODIVERSITY**

According to one interview participant, fire is “the most powerful land management tool that land managers in the Northern Territory have at their disposal.” However, the effectiveness of this tool comes into question when some people are not up-to-date on the best fire management practices or when others are completely apathetic towards learning about successful methods. Even when equipped with knowledge of the best current fire management practices, fire may be ineffective when everyone involved is not on the same page and working together towards similar outcomes.

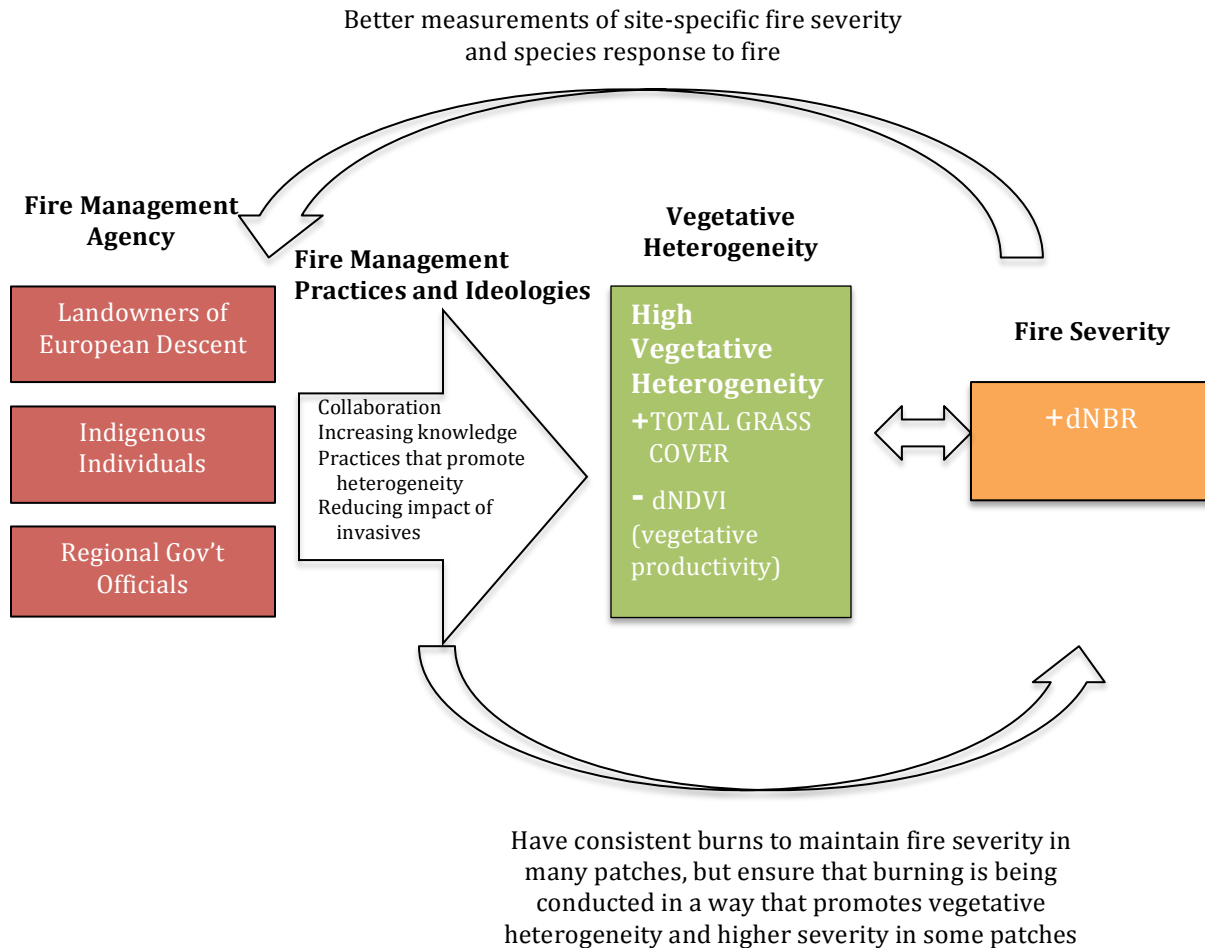
While there is extensive research from universities and Australian institutions such as the Commonwealth Scientific and Industrial Research Organization, the information it produces oftentimes does not get translated down to the people who are actually managing fire. Many interviewees echo this sentiment. Participant #4, the indigenous consultant, even stated that “for the average white Australian, [there] is almost zero knowledge about aboriginal people and their relationship with the land.” Both land managers and the public on local, regional, and national levels are essentially not receiving the message they need to hear. Land managers should not only be aware of the best fire management practices according to the latest research, but they should also know how to implement them on a site-specific level by creating unique fire regimes for the areas they are managing. Additionally, when the public is aware of how important an issue fire management is in the Northern Territory, it is more likely that support for government

funding would increase. In sum, I argue that communicating fire management knowledge positively influences species and habitat welfare by providing resources both on the ground and through government infrastructure.

Interestingly, fire managers may need to be just as concerned about their next-door neighbors as they are about how their own property is managed. A lack of knowledge or apathy towards fire management can be seriously problematic when this describes the ability or attitude of one's neighbor. Over half of my participants described a situation in which an intense, uncontrollable fire came onto their property because the land owners adjacent to them were not being careful, did not know what they were doing, or did not care about employing proper fire management practices.

While implementing the actual positive fire management practices themselves is helpful for species such as the RBFW, the only way RBFWs will be truly benefited is if land managers across all groups and throughout similar habitats of the Northern Territory communicate and collaborate about how to use fire as a tool to manage Country. It may seem like a simple approach, and it has been successfully implemented (Lewis 1989), but those involved in fire management have much more to change in order to truly approach fire management as a *landscape* process that also varies between sites in a naturally and artificially heterogeneous environment. Barriers built upon past stigmas and pride need to be broken, and people need to be just as adaptive as the plants and animals living on their property. Based on my results and interpretation, RBFWs will benefit greatly from this approach (Fig. 4a).

**Figure 4a. Complete positive framework model for RBFW occupancy and fire management practices.**



#### 4.6. APPLICATION OF FINDINGS ON A MULTI-SPECIES AND GLOBAL SCALE

While land managers should look beyond their own land and think about fire management on a landscape scale, they should also emphasize a multi-species and global interpretation of how land should be managed.

For many years, studies focusing on species response to fire remained restricted to particular species such as the Gouldian finch (*Erythrura gouldiae*; Tidemann 1984). Even though a large amount of comprehensive, influential research stemmed from this work, it placed a very

narrow lens on how researchers and land managers should view species and their relationship to fire and how it is managed. It is important to note that while one species may benefit from the practices and ideologies mentioned in this study (such as the RBFW; Fig. 4a), not all species have similar responses to fire or fire management. By focusing on other species like the RBFW, more is being added to current fire management literature that will in turn lead to practices and regimes that have a better understanding of diverse species responses. In the future, studies on more types of organisms in heterogeneous habitat should be conducted to create a more complete picture of the complex relationships between fire, humans, the landscape, and endemic species.

Ultimately, a collaborative and communicative approach in fire management should be applied on the scale of the global landscape. Tropical savanna habitats exist in the Mediterranean and Western U.S., and these locations have similar ecological and management issues in relation to fire (Thomas et al. 2010) Additionally, many parts of central and southern Australia are also experiencing an increase in intense fires when and where this would normally not occur, as indicated in many current news articles (BBC 2014). This is largely due to climate change as conditions become more extreme worldwide, and the effects of these changes are likely to worsen in the future (Fitzsimmons et al. 2012). Therefore, it is extremely important now more than ever to understand the intricacies of fire management first on a site- and species-specific scale in order to appreciate how ideologies and practices can be applied on a global level.



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## 6. Appendix

### 6.1. INTERVIEW PROTOCOLS

#### 6.1.1. Interview Questions for Aboriginal Representatives

1. If known, approximately how long have tribes within the region used fire to cause land cover change?
2. How often do regional tribes conduct prescribed burns on the area? Has this changed from past patterns of aboriginal use of fire on the land?
3. For what specific reasons have aboriginal tribes within the region conducted prescribed burns in the past and present? Have these reasons changed overtime?
4. Is there a specific type(s) of animal and/or plant that aboriginal tribes in general are trying to target? If so, for what reasons are these species being targeted?
5. What is your opinion on using prescribed burns on tropical savanna habitat? Has your opinion changed over time, and if so, how?
6. How do aboriginal tribes manage prescribed burns that unintentionally extend beyond their control? Does this kind of event happen often?
7. Have members of aboriginal tribes recognized any change in quantity and/or severity of fires in the region over the years?
8. How is the current relationship between regional aboriginal groups, local landowners and regional government officials when handling prescribed burns set by either party or by aboriginal groups themselves?
9. Have you or any aboriginal group members noticed a change in the quantity and/or diversity of the flora and fauna in the region over the years? If so, what kinds of changes in wildlife have been observed?
10. In general, how do you and the popular opinion within regional aboriginal groups see prescribed burn policies in the local area and in the entire Northern Territory evolving in the next ten years? What are your recommendations for improving local and regional land management to benefit the local human population and/or native plants and non-human animals?

### 6.1.2. Interview Questions for Regional Government Officials

1. How do regional government officials oversee the management of tropical savanna habitat using prescribed burns?
2. What is the reasoning of regional government officials behind using prescribed burns in common practice for land management purposes?
3. What pros and cons does the regional government recognize in regularly using prescribed burns?
4. Is there a specific type(s) of animal and/or vegetation that the regional government is trying to target?
5. What is your opinion on using prescribed burns on tropical savanna habitat? Has your opinion changed over time, and if so, how?
6. How does the regional government manage prescribed burns that unintentionally extend beyond your control? Does this kind of event happen often?
7. Have regional government officials recognized any change in quantity and/or severity of fires in the region over the years?
8. How is the regional government's relationship with local landowners and aboriginal groups when handling prescribed burns set by either party or by government officials themselves (either directly or indirectly)?
9. Have you or other regional government officials noticed a change in the quantity and/or diversity of the flora and fauna in the region over the years? If so, what kinds of changes in wildlife have been observed?
10. In general, how do you and the popular opinion within your organization see prescribed burn policies in the local area and in the entire Northern Territory evolving in the next ten years? What are your recommendations for improving local and regional land management to benefit the local human population and/or native plants and non-human animals?



### 6.1.3. Interview Questions for Landowners of European Descent

1. How long have you owned your property in Batchelor, NT?
2. How often do you set prescribed burns on your property?
3. For what specific reasons do you use fire to manage your property?
4. Is there a specific type(s) of animal and/or vegetation that you are targeting when you set fire to your land?
5. What is your opinion on using prescribed burns on tropical savanna habitat? Has your opinion changed over time, and if so, how?
6. Is there anyone who encourages you to conduct prescribed burns on a regular basis (i.e. friends, neighbors, local government officials, etc.)?
7. What means (i.e. equipment, resources, etc.) do you use to control the fires you purposefully set on your property?
8. Have you ever set a fire on your property that unintentionally extended beyond your control? If so, what did you do and who did you contact to help you handle the situation?
9. How often does a fire come through your property that was not originally set by you? Has the quantity and/or severity of these fires changed over the years?
10. How is your relationship with local government officials who focus on land management and prescribed burning?
11. Have you noticed a change in the quantity and/or diversity of the flora and fauna on your property over the years? If so, what kinds of changes in wildlife have you been noticing?
12. How do you see prescribed burn policies in the local area and in the entire Northern Territory evolving in the next ten years? What are your recommendations for improving local and regional land management to benefit the local human population and/or native plants and non-human animals?

## 6.2. TABLES FOR OCCUPANCY MODELING

**Table 6.2.1. Summary of sampling covariate model AIC-related values.**

Model	# of Parameters	AIC <sub>c</sub>	ΔAIC	AIC wgt
<b>1 group, Constant P</b>	<b>2</b>	<b>189.95</b>	<b>0</b>	<b>0.52</b>
1 group, Survey-specific P	3	191.81	1.86	0.20
psi(.),p(Julian+high_grass)	5	193.09	3.14	0.11
psi(.),p(highgrass)	3	194.47	4.52	0.054
psi(.),p(Julian+high_grass+time)	7	195.35	5.4	0.035
psi(.),p(Julian)	3	195.50	5.55	0.032
psi(.),p(Julian+Time)	5	195.53	5.58	0.032
psi(.),p(time)	3	196.54	6.59	0.019

**Table 6.2.2. Summary of site covariate model AIC-related values.**

Model	# of Parameters	AIC <sub>c</sub>	ΔAIC	AIC wgt
psi(total_grass+saplings+dNDVI+NBR),p(.)	5	183.45	0	0.3013
psi(dNDVI+dNBR+total_grass+saplings+high_grass),p(.)	6	184.14	0.69	0.2134
psi(saplings+dNDVI+dNBR),p(.)	4	185.09	1.64	0.1327
psi(dNDVI+dNBR+saplings+high_grass),p(.)	5	186.64	3.19	0.0611
psi(dNBR+dNDVI),p(.)	3	186.78	3.33	0.057
psi(canopy_cover+dNBR+dNDVI+saplings),p(.)	5	186.86	3.41	0.0548
psi(dNBR+dNDVI+Total_grass),p(.)	4	187.57	4.12	0.0384
psi(High_grass+dNDVI+dNBR),p(.)	4	187.99	4.54	0.0311
psi(High_grass+total_grass+dNDVI+dNBR),p(.)	5	188.21	4.76	0.0279
psi(dNDVI),p(.)	2	189.86	6.41	0.0122
<b>1 group, Constant P</b>	<b>2</b>	<b>189.95</b>	<b>6.5</b>	<b>0.0117</b>
psi(saplings),p(.)	2	191.28	7.83	0.006
psi(canopy_cover),p(.)	2	191.34	7.89	0.0058

**Table 6.2.3. Weighted slopes and standard errors for  $\Sigma\psi$  across models for site covariates**

Site Covariate	AIC <sub>c</sub> Weight	Weighted Slope	Weighted Standard Error
dNDVI	0.93	-0.83	0.67
dNBR	0.92	+0.80	0.65
Saplings	0.77	+0.58	0.50
Total Grass	0.58	+0.43	0.38
High Grass	0.33	-0.13	0.21
Canopy Cover	0.0548	+0.030	0.032