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The Historical Ecology of Queensland's Australian Saltwater Crocodile (Crocodylus porosus)

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ABSTRACT

Human wildlife conflict is a critical aspect of many societies, as it often plays a large role in government decisions. The iconic saltwater Australian crocodile (*Crocodylus porosus*) is one example of a species that has become the subject of human-wildlife conflict in Queensland, Australia. Decades of intensive hunting in Queensland, beginning at the time of the Second World War, drastically depleted crocodile populations, leading to a federal embargo on crocodile exports in 1972 and their protection in Queensland in 1974. Since protection, populations appear to be recovering with increasing densities in the north and increased sightings along the southernmost edge of their observed range. However, research has indicated that population recovery is slower than in the adjacent Northern Territory, although the drivers of this slow recovery and southern sightings remain unknown. Two potential drivers include range expansion due to climate change or re-colonization of areas from which they were previously extirpated. This study uses a variety of spatial and temporal density analyses in relation to human population size to examine the abundance and range status of crocodiles in Australia. It compares the distribution of sightings, nests and attacks over pre-exploitation (1871-1944), heavy exploitation (1945-1971) and post-exploitation (1972-2015) time periods to assess three related hypotheses: First, crocodile populations are expanding outside of known historical ranges. Second, crocodile populations have recovered to historical baseline abundances in areas that abut regions of high human population density. Third, crocodile attack rates have increased over time relative to human population size. While crocodile ranges do not appear to be expanding, they do heavily overlap with the highest anthropogenically altered areas. Furthermore, although crocodile abundance is difficult to characterize, attack rates have remained relatively low since the pre-exploitation period. These findings suggest that coastal development and crocodile removal plans may be driving crocodiles outside of natural habitat ranges and that the recent southern sightings likely represent the re-colonization of crocodiles in former southern ranges. This study aims to provide management with historical information of crocodiles in relation to current trends to aid in successful management that allows crocodile populations to recover, while maintaining low instances of human-crocodile conflict.

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CHAPTER ONE: LITERATURE REVIEW

Saltwater Crocodile Background

Saltwater crocodiles (*Crocodylus porosus*) are the largest extant reptiles (Campbell et al. 2014) and part of one of the oldest constant lineages in the world (Caldicott et al. 2005). This species has one of the most widely distributed ranges of all crocodilians, extending from India and Sri Lanka, throughout most of southeast Asia, to northern Australia (Webb et al. 2010). In Australia, it is found in the northern regions of Queensland, the Northern Territory and Western Australia (Figure 1). It occupies a variety of habitats including coastal, estuarine, freshwater and marginal terrestrial ecosystems, and serves as the apex predator within these ecosystems (Campbell et al. 2015). The saltwater crocodile's conservative life history traits render it susceptible to overexploitation (Lang 1987a). Crocodiles are long-lived and have long reproductive lifespans of several decades. They take several years to reach sexual maturity and although they produce large egg clutches, many of the eggs do not hatch and survival of the hatchlings is comparatively low due to aggressive interactions, such as predation. Although adult survivorship is high in natural populations, over the past century saltwater crocodiles in Australia have faced numerous threats, including exploitation and habitat destruction, which have resulted in severe population declines (Grigg and Kirshner 2015).

The saltwater crocodile was protected from hunting beginning in the 1960s and 1970s. During the past few decades, the Northern Territory populations have rebounded, but in the adjacent and more populous state of Queensland, recovery is lagging (Letts 1987, Read et al. 2004b). While some stakeholders claim that populations in Queensland are reaching healthy levels and are expanding in range, research examining baseline crocodile populations is lacking, so it is difficult to ascertain if this claim is true (Grigg and Kirshner 2015). Furthermore, some citizens and resource managers fear that, due to the large coastal human populations in Queensland, an increase of attacks on humans may occur if recovery succeeds. Increased crocodile sightings have occurred in southern locations, but it is unclear if these sightings are due to range expansion due to climate change or recolonization of areas from which crocodiles were previously extirpated.

This project aims to tackle some of the complex social, political, and environmental implications of human-crocodile conflict by improving the understanding of historical crocodile ranges, current populations, and crocodile attack rates through time. Specifically, it addresses three related research questions:

1. Are crocodiles expanding outside of known historical ranges, possibly in response to climate forcing?
2. Have crocodile populations recovered to historical baseline abundances in areas that abut regions of high human population density?
3. Have crocodile attack rates increased over time relative to human population size?

This project takes a historical ecological approach and uses historical data from newspapers (1871 – 1957, National Library of Australia 2015), a voluntary reporting program (2010 – 2015, Department of Environment and Heritage Protection 2016) and a crocodile attack database (1868 – 2015, CrocBITE 2016).

Figure 1. This map displays the relative location of Queensland (the study site), the Northern Territory and Western Australia, the Australian states in which saltwater crocodiles occur (Adapted from: Street Map - Australia n.d.).

Threats Facing Saltwater Crocodiles

Exploitation

Exploitation can take various forms, including commercial harvest, subsistence harvest and recreational, or “sport” hunting. Populations of apex predators tend to be highly susceptible to impacts from exploitation for multiple reasons. First, apex predators, such as crocodiles, typically have conservative life history traits, including high adult survivorship, which renders a population sensitive to increased levels of adult mortality. The home ranges of apex predators and types of their prey often place them in direct contact with humans (Treves and Karanth 2003), and thus vulnerable to exploitation.

Substantial hunting of saltwater crocodiles in Queensland began in the 1930s (Grigg and Kirshner 2015), with the highest levels occurring from the 1940s through the mid-1960s (Letts 1987). The development of a large international market for crocodile skins and other products (Taplin 1987), coupled with improved hunting and shipping technologies (Grigg and Kirshner 2015), drove exploitation and, after just two decades, populations in Queensland reached extremely low levels relative to their former abundance (Taplin 1987). By the late 1960s, the Australian Fauna Authorities recognized the depletion of saltwater crocodile populations as the industry virtually collapsed (Letts 1987). Although exploitation had already ceased in areas where saltwater crocodiles were severely depleted, the potential for intensive exploitation effectively ended in 1972 when the Commonwealth Government banned the export of crocodile skins and products (Taplin 1987). Since then, crocodile populations have been struggling to rebound. However, other anthropogenic threats, such as habitat alteration, have inhibited recovery (Lang 1987a).

Habitat Alteration

Across the world, human population expansion has led to intensified agriculture and thus modified habitats of various species (Woodroffe 2000). Destruction of estuarine and coastal habitat has been one of the principal causes of historical changes in population size and distribution of large predators around the world (Lotze and Worm 2009). In 2005, Australia was the only country with a developed first world economy that fell into the top 20 land-clearing nations (Lindenmayer and Burgman 2005). Within Australia, Queensland in particular has faced severe habitat threats due to extreme land clearing in the last 50 years (McAlpine et al. 2009). If Queensland were a country, in 2005 it would have ranked ninth worst in the world in terms of land clearing, with over 425,000 hectares cleared each year (Lindenmayer and Burgman 2005). Between 1921 and 1971, extremely high rates of urbanization occurred in Queensland, and in more recent years, coastal cities in particular have shown strong growth, mostly due to increased tourist activities (Queensland Government 1998, Bohnet and Pert 2010). These coastal cities tend to fall into the range of saltwater crocodile habitat, which intensifies the probability of attacks on humans while reducing viable habitat (Taplin 1987).

Coastal urban development severely degrades wetlands through mangrove removal, heavy recreational usage of waterways and substantial river bank erosion (Taplin 1987). Research attributes the low crocodile density in Queensland mostly to such poor habitat quality (Taplin 1987, Fukuda et al. 2007). The leading land usage of potential saltwater crocodile habitat is for beef cattle grazing, which substantially alters the ecosystem and causes damage to potential saltwater crocodile nesting areas. Farming of sugar cane, rice, tropical fruits and vegetables has also played a large role in clearing important habitat (Taplin 1987). The resulting reduced quality and quantity of resources within saltwater crocodile habitats ultimately affects the growth and the reproduction of saltwater crocodiles, diminishing the potential for their populations to rebound from other anthropogenic threats (Lang 1987a), such as climate change (Travis 2003).

Climate Change

Across the world, species' ranges are shifting in response to climate change. Chen et al. (2011) estimated that species have moved away from the equator at a median rate of 16.8 km/decade, with substantial variation among species. Over the past century, Australia has warmed by about 1.0 degree Celsius and there has been an increase in the frequency of hot days and nights (Nicholls 2006, Deo 2011). Within Australia, the most severe warming has occurred since the 1950s in eastern Australia, which is where Queensland is located (Nicholls 2006). At present, crocodilians can withstand the highest temperatures recorded in aquatic habitats (Grigg and Kirshner 2015). Therefore, while climate change will not likely drive saltwater crocodiles from the equator, it may allow their range to expand further south (Fukuda et al. 2007) as it is currently the cold winters of these southern latitudes that limit expansion (Taplin 1987). Because of the potential for changes in ecosystem function, economic opportunities, or social conflicts, it is important to know if a species is extending its range (Robinson et al. 2015).

While climate change may positively benefit saltwater crocodiles by allowing their range to expand, it will also likely have many negative effects on the species. Crocodiles are ectotherms so their body temperatures are highly dependent on the temperature of their surrounding environment. Temperatures above 35 degrees Celsius have been shown to be lethal to crocodiles (Grigg and Gans 1993), so extremely hot days could pose a threat. Additionally, studies have indicated that increased temperatures reduce digestion time and hence decrease energy conservation in crocodiles (Grigg 1978, Grigg & Gans 1993, Lang 1987). Temperatures above 33 degrees Celsius have also been shown to decrease sustained swimming speed for crocodiles (Elsworth et al. 2003). These factors will particularly impact large individuals, which may heat rapidly but cool more slowly (Fraser and Grigg 1984). Finally, temperature also helps to determine the sex of offspring in saltwater crocodiles, so increasing temperatures may result in shortages of females, which could severely impact the survival of future populations (Webb et al. 1987, Grigg and Kirshner 2015).

Climate change may also further contribute to human-crocodile conflict. First, warmer temperatures have been shown to cause saltwater crocodiles to grow faster and to larger sizes (Grigg and Kirshner 2015). This could pose a problem because the difference in body mass between crocodile and victim represents the most influential factor in saltwater crocodile attacks leading to human fatalities (Fukuda et al. 2015). Furthermore, if ranges expand into sub-tropical regions of Australia, citizens with no previous experience with crocodiles will need to learn to co-exist with saltwater crocodiles, and their initially sub-optimal vigilance will likely lead to increased attacks (Fukuda et al. 2007). As climate change continues to escalate, is it likely that its effects will be further exacerbated by habitat loss, which can drastically reduce a species' ability to survive climate shifts (Travis 2003)

Predator Recovery and Human-Wildlife Conflict

Wildlife population recovery can occur in response to various mitigation measures, including habitat restoration, breeding programs and reintroductions. Though recovery of wildlife can greatly improve ecosystem health, which in turn can benefit people, it can also result in increased human-wildlife conflict (Messmer 2000). Because apex predators occupy similar ecological roles as humans, it often places them in competition for both resources and space (Yodzis 2001, Treves and Karanth 2003). Among conservation biologists, the interest in human-wildlife conflict has increased over time, with the number of scientific articles published about human-wildlife conflict significantly increasing over the last ten years (Dickman 2010). This can, in part, be attributed to the importance of understanding these conflicts, which have social, economic and political implications (Messmer 2000, Dickman 2010). Collaborative co-management by affected groups is conducisve to reducing these conflicts (Treves et al. 2006), but opposing interests render its success extremely difficult (Dickman 2010). Various stakeholders often blame each other in human-wildlife conflict scenarios, and it thus evolves into a human-human conflict (Dickman 2010).

In Australia, the saltwater crocodile is the only large terrestrial predator that threatens humans (Butler 1987) and since the 1970s, attack rates have been increasing in Queensland (Sideleau and Britton 2013). However, this increased attack rate can be attributed to various factors. For example, even though public awareness campaigns exist, humans often assert themselves into dangerous situations involving saltwater crocodiles when under the influence of alcohol or driven by the promise of high fish catches (Grigg and Kirshner 2015). Despite the fault of many humans in human-crocodile conflict scenarios, management has continually responded by non-lethally removing saltwater crocodiles from human-populated areas (Walsh and Whitehead 1993). This systematic removal of organisms is termed culling, whereby they are removed with the intention to solely affect the remaining system, rather than for exploitative purposes (Yodzis 2001).

However, while crocodiles are intended to be removed non-lethally, they have displayed changes in blood chemistry when captured, which may contribute to the post-capture mortality syndrome that is often observed in large individuals (Seymour et al. 1987). Because large individuals are often the animals targeted for culling, it is likely that this management practice could impact the social organization of the saltwater crocodile population. Large males tend to dominate breeding groups and females submit to these dominant males (Lang 1987a); thus, overall social structure, and possibly breeding success, of saltwater crocodiles could change if removal of large individuals were to persist over long periods of time.

Government policies of culling and removing saltwater crocodiles have come under scrutiny as they often favor the improvement of the public's perception of risk instead of actually reducing the risk. Termed "action bias," this propensity to do anything, even if it is counterproductive, rather than doing nothing, has influenced policy decisions (Neff 2012). Thus, as many Australian citizens fear the recovery of saltwater crocodile populations, Australian management, particularly in Queensland, has met these concerns by implementing strategies that may be further inhibiting crocodile recovery (Lang 1987a, Seymour et al. 1987). The existence of such management strategies reveals the importance of improving public perception of apex predators and of addressing conflicts more directly. Human-crocodile conflict may be mitigated by determining when and where humans and saltwater crocodiles overlap spatially and then minimizing their interactions (Campbell et al. 2014). It is possible that coexistence may be improved by enhancing human awareness and perception of saltwater crocodiles through management.

Management of Australian Saltwater Crocodiles

The management of predators like saltwater crocodiles can be challenging politically even more so than scientifically (Treves and Karanth 2003). However, some areas, like the Northern Territory of Australia, have been successful in their management strategies (Letts 1987). In 1964, the Northern Territory enacted legal protection for saltwater crocodiles following Western Australia's protection in 1962 (Table 1, Read et al. 2004b). Since 1975, the Northern Territory's government has monitored saltwater crocodiles through annual surveys of over 670 km of the territory's rivers (Campbell 2016). Its effective management programs, which include conservative utilization through sustainable harvest, attention to habitat, intensive public education and close work with aboriginal and commercial fishermen, have allowed saltwater crocodile populations to successfully recover (Letts 1987). This now healthy population is harvested sustainably by citizens in the Northern Territory, and has led to a thriving and growing industry that is predicted to generate approximately $50 million per year over the next five years (Campbell 2016).

Table 1. The key saltwater crocodile management events through time for Queensland, Australia.

Event	Date	Source
Aboriginals first arrive in Australia; human-crocodile conflict first begins	38,000 B.C.	Letts 2004
Substantial hunting of saltwater crocodiles begins	1930s	Grigg and Kirshner 2015
Intensive commercial harvest of saltwater crocodiles in Queensland begins	1945/46	Taplin 1987
Protection of saltwater crocodiles in Western Australia	1962	Letts 2004
Protection of saltwater crocodiles in Northern Territory	1964	Letts 2004
Commonwealth Government places embargo on export of saltwater crocodile products	1972	Taplin 1987
Declaration of the Queensland Fauna Conservation Act; crocodiles are protected in Queensland	1974	Letts 2004, Read et al. 2004a
East Coast Crocodile Management Program introduced to Queensland	1987	Read et al. 2004a
Intensive Management Area for Crocodiles program begins; Croc-Wise program started to increase public awareness about crocodiles	2001	Read et al. 2004a
Liberal National Party begins new Crocodile Management Plan	2013	Department of Environment and Heritage Protection 2013
Current Environment Minister calls for review of current plan	2015	Elks 2015

Queensland adopted saltwater crocodile protection management in 1974, making it the final saltwater crocodile populated state to do so (Table 1, Letts 2004, Read et al. 2004b). The Queensland government has stated that its two primary goals for saltwater crocodile management are to maintain viable populations across their natural range and to provide public safety and ecologically sustainable use (Read et al. 2004b). Crocodile expert Grahame Webb has advocated for the support of scientifically based commercialization of crocodiles in order to encourage their conservation. However, in contrast to the Northern Territory, where saltwater crocodile skins and meat can now be sold sustainably (Grigg and Kirshner 2015), utilization in Queensland is restricted to captive breeding on farms (Webb et al. 2010). This strategy decreases the incentive for citizens to support saltwater crocodile recovery (Read et al. 2004b).

The Queensland government has focused on removal strategies, as opposed to scientific research directed at understanding abundance and range of the population. Although the government began conducting spotlight surveys of crocodile populations in 1972, these surveys have been sporadic and not properly replicated, rendering the data of little value (Campbell 2016). For example, Dwyer et al. (2012) found that the most recent surveys conducted in Queensland (2007 and 2009/2010) did not include enough waterways and did not occur for long enough periods of time to detect significant change in the size of saltwater crocodile populations. Management has primarily focused on saltwater crocodile removal strategies. For example, the current Crocodile Management Plan focuses on reducing human interactions with saltwater crocodiles by dividing possible areas of occurrence into three different removal zones (Table 2, Department of Environment and Heritage Protection 2013). However, attaining coexistence is stated as an important long-term conservation strategy (Taplin 1987).

Stakeholders' opinions of this policy vary in Queensland. Some have expressed their support for the plan, believing that it will allow people to visit the beaches more often without the threat of crocodiles (Solomons 2013, Elks 2015). However, others have stated that they think the best management strategy is to cull all crocodile individuals that are bigger than two meters. In contrast, many scientists oppose culling and removal strategies because of their impacts on social dynamics of the species (Solomons 2013) and because such strategies can lull the public into a false sense of security (Neff 2012).

After the most recent crocodile attack in April 2015, the current Environment Minister stated that the government would review the crocodile management plan. He recognized that people have strong opinions on both sides of the issue, with some believing that removal threatens the species and others calling for the removal of even more crocodiles (Elks 2015). This announcement renders the present an opportune time for crocodile research, as applied research has been shown to be more successful when there are near-term management goals (Messmer 2010). Furthermore, since government surveys of saltwater crocodile populations have been of poor quality and lacking in number, with the most recent having been conducted in 2009/2010 (Dwyer et al. 2012), it is crucial that more research be conducted to assess the current status of these crocodiles in relation to historical baselines (Taplin 1987).

Table 2. The goals of current crocodile removal zones in Queensland, Australia (Department of Environment and Heritage Protection 2013).

Zone	Goal
One	Prevent crocodiles from entering by using physical barriers between zone and known saltwater crocodile population and remove any individuals that do enter
Two	Remove any individuals that are over two meters in length or that display aggressive behavior once a sighting is confirmed
Proactive Removal Zone (within Zone Two)	Remove all individuals regardless of size and behavior on a proactive basis to the greatest extent possible
Three	Only remove individuals that have attacked or behaved aggressively towards a human, have posed a threat to human safety due to their location or behavior, or have passed a prevention barrier and are behaving aggressively towards stock, working dogs or aquaculture fisheries resources

Status of Saltwater Crocodiles in Queensland

The range of saltwater crocodiles mainly includes coastal areas north of the Fitzroy River, with infrequent sightings occasionally being reported south of this river (Donaghey 2015). The southernmost extent of this range has typically been cited as the Boyne River (Figure 2, Queensland Parks and Wildlife Service 2007), although the distribution of this population in Queensland is spatially variable and dependent on the availability of suitable nesting habitat (Read et al. 2004a). Surveys around 1999 and 2007 revealed no evidence of saltwater crocodiles near the Boyne River (Read et al. 2004a,

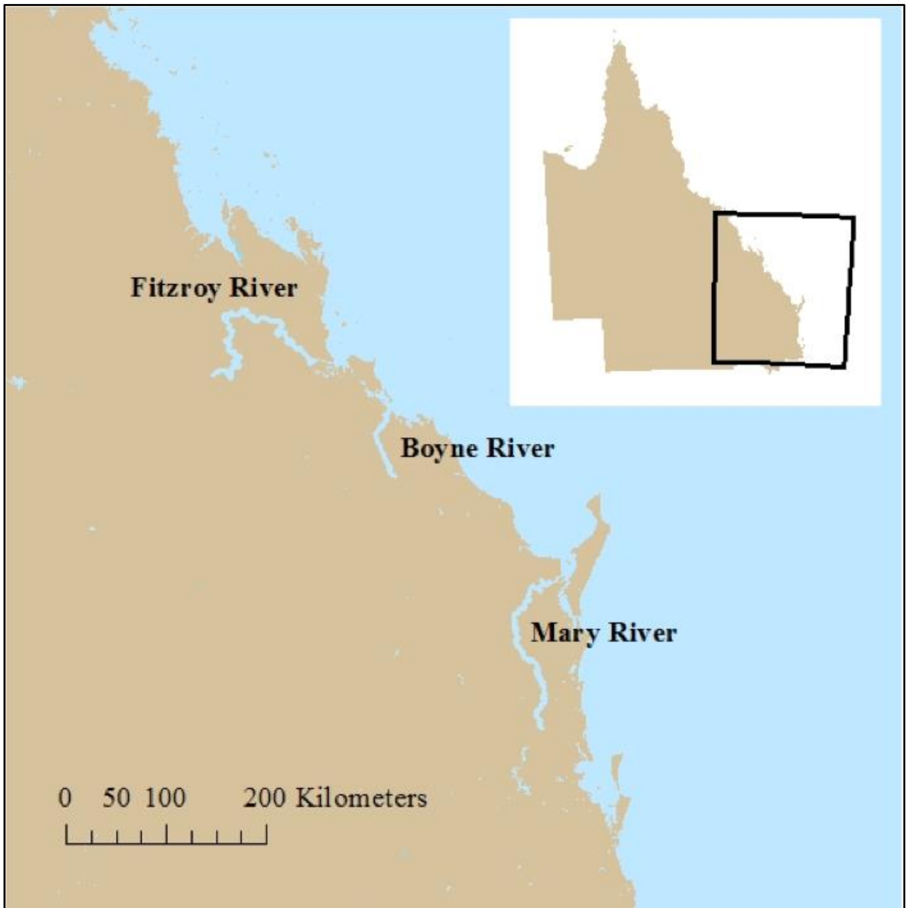

Figure 2. The location of the Fitzroy, Boyne and the Mary Rivers, which have all been described as the "southernmost extent" of crocodiles at some point in time.

Queensland Parks and Wildlife Service 2007). However, in more recent years, saltwater crocodiles have been sighted in the Mary River, which is substantially farther south than the Boyne. In May 2015, a confirmed sighting occurred at the most southern location in recent history, representing the fourth occurrence in the Mary River in recent years. Though the driver of these southern sightings is unknown, scientists believe that they could be due to rising temperatures and it is likely that they will continue to increase in frequency. As citizens in these areas are unfamiliar with saltwater crocodiles, it is also possible that the presence of saltwater crocodiles in this area could lead to increased human-crocodile conflict (Donaghey 2015). Understanding the spatial distribution of saltwater crocodiles in Queensland is necessary for balancing the needs of this species while simultaneously reducing human-crocodile conflict (Read et al. 2004a).

The current population size of saltwater crocodiles in Queensland is unknown (Campbell 2016). However, while the survey effort has been much lower in Queensland than in the adjacent Northern Territory, the data that do exist suggest that population recovery has been much slower (Grigg and Kirshner 2015), with one survey citing relative abundance figures as 20 times lower than in the Northern Territory (Queensland Parks and Wildlife Service 2007). Furthermore, the most recent survey in 2009/2010 revealed that the population was skewed towards smaller individuals with 73 percent of sighted individuals being equal to or less than 2.0 meters in total length (Queensland Government 2011). When saltwater crocodile attacks occur, citizens are often quick to jump to the conclusion that numbers are increasing. However, reliable information about trends in numbers does not exist, and therefore it is impossible to verify these assumptions (Grigg and Kirshner 2015). Information concerning the effects of the current crocodile removal policy, how this population has changed since the ban on hunting (Campbell 2016), and estimates of former populations densities is severely lacking and would be highly valuable for better understanding the dynamics of this population (Taplin 1987).

Historical Ecology

In 1995, Pauly (1995) coined the term “shifting baseline syndrome,” whereby a shift occurs in the perception of “natural” ecosystems towards more degraded states. In order to overcome this phenomenon, it is important to understand the baseline of species and ecosystems in terms of abundance and range. However, most monitoring projects historically have not begun until populations have already started showing signs of decline (Bonebrake et al. 2010). Therefore, historical ecology research assessing long-term baselines is necessary in order to bridge this gap (Mcclenachan et al. 2012, Kittinger et al. 2013). Understanding the historical baseline of a population can help inform management (McClenachan et al. 2012) by establishing a marker for successful population recovery (Kittinger et al. 2013). For example, Lotze and Worm (2009) reviewed 256 records from historical time periods (100s to 1000s of years) and exploited time periods across the world and found that exploited populations of large marine mammals, birds, reptiles and fish declined approximately 89 percent from historical abundance levels.

Assessing “virgin” states of populations can be extremely difficult (Pinnegar and Engelhard 2008), but various methods exist for trying to ascertain numbers that are close. Population information is increasingly being extracted from new types of sources (Bonebrake et al. 2010), including, but not limited to, historical reports, maps, logbooks, catch records, cookbooks and restaurant menus (Lotze and Worm 2009). However, many historical studies still lack long-term perspective, with only about 15 percent studying populations beyond 100 years. Reptiles account for only about six percent of population trend studies (Bonebrake et al. 2010). In the case of saltwater crocodiles, Grahame Webb made a comprehensive effort to estimate pre-hunting populations in the Northern Territory, but no baseline abundance data exist for Queensland (Grigg and Kirshner 2015).

Importance of Study

Apex Predator Importance

Apex predators are critical components of ecosystems as they help prevent trophic cascades through top-down control (Brook et al. 2012). In marine, terrestrial and freshwater ecosystems worldwide, releases of mesopredators have been attributed with declines in apex predator abundance (Estes et al. 2011). Furthermore, the loss of apex predators can indirectly affect ecosystems through behaviorally mediated indirect interactions (Heithaus et al. 2008). For example, in Australia, when dingoes were controlled, feral cats increased in abundance and were able to optimize their hunting behavior (Brook et al. 2012). Saltwater crocodiles fill this vital apex predator role in their aquatic and tropical wetland ecosystems, which support both fish and game (Taplin 1987).

This indirect value of the role that the saltwater crocodile plays in its ecosystem, combined with its direct value as an exploitative resource, may act together as powerful incentives to support the conservation of this species (Butler 1987). For example, in the Northern Territory, the commercial value of saltwater crocodile hides has now improved its conservation by creating monetary incentives for sustainable use. The products that present direct exploitative value include saltwater crocodile skin, meat and curios, although the species is also valuable for trophy hunting. The species also serves as a valuable tourist attraction as guided ventures to see saltwater crocodiles have increased (Grigg and Kirshner 2015). By providing citizens with evidence that saltwater crocodiles hold substantial economic value, while educating them that “living with crocodiles” is possible, resource managers can achieve successful long-term conservation (Taplin 1987). However, extensive historical knowledge of crocodile range, abundance and human interactions is key to attaining this success.

Aims of Study

This study synthesizes historical and current information available on saltwater crocodiles in Queensland, Australia to provide insights into the complex social, political and environmental implications of the human-crocodile conflict. Results of this research should help resource managers address these problems by improving the understanding of historical crocodile ranges and the current distribution and status of populations and attack rates. This paper summarizes information from a historical newpaper database (1871-1957, National Library of Australia 2015), a voluntary reporting program database (2010-2015, Department of Environment and Heritage Protection 2016) and a crocodile attack database (1868-2015, CrocBITE 2016) to address three related hypotheses: First, crocodile populations are expanding outside of known historical ranges. Second, crocodile populations have recovered to historical baseline abundances in areas that abut regions of high human population density. Third, crocodile attack rates have increased over time relative to human population size. Each subsequent chapter addresses one of these three hypotheses. This research should be considered preliminary, as approximately 25 percent of available historical data have been collected and analyzed to date.

CHAPTER TWO: RANGE

Hypothesis: Crocodile populations are expanding outside of known historical ranges.

Methods

Sighting and Nesting Data Collection

Sighting and nesting data were collected from three different sources: Trove, a database of historical Australian newspapers that have been digitized by the National Library of Australia (1871-1957, National Library of Australia 2015), CrocWatch, a voluntary reporting program database maintained by the Queensland Government Department of Environment and Heritage Protection (2010-2015, Department of Environment and Heritage Protection 2016) and CrocBITE, a crocodile attack database created by a number of crocodile researchers (1868-2015, CrocBITE 2016, Table 3). All crocodile sightings or nests that occurred in Queensland, Australia, were extracted from CrocWatch and CrocBITE. For Trove, historical newspapers were chosen based on their location and years of operation to cover the widest possible timeframe and area across the state. Nineteen newspapers (Appendix I) were searched with criteria in which the results were articles containing the word "crocodile," but without the word "mine," so to exclude references to a gold mine in Queensland named "Crocodile Mine." This yielded over 10,000 individual articles which were reviewed and from which observations of crocodiles were extracted.

Table 3. The number of crocodile sightings identified from each source, and the range of years with data used from that source.

Source	**Years**	**Number of Sightings**
Trove	1871-1957	556
CrocWatch	2010-2015	1,733
CrocBITE	1868-2015	55

Historical sightings were only included in the analysis if the crocodile was passively sighted to keep effort constant through time as CrocWatch only represents passive sightings. Therefore, all crocodiles sighted during crocodile hunting expeditions were excluded. Furthermore, all indirect evidence of crocodiles, such as bellowing, tracks or bite marks, was omitted (with the exception of crocodile nests), to assure accuracy of identification and location of animals. The location of each sighting was determined by entering all reported location information into Google Maps (Google 2016). The most accurate location for the sighting was clicked and the latitude and longitude of that location were recorded. The certainty of each location was then ranked based on the available location data (Table 4) and only locations with a certainty rating of two or higher were included in analysis.

Table 4. The criteria for ranking the location certainty of crocodile sightings across Queensland.

Rank	Criteria
Zero	Location for the sighting could not be determined
One	The location could be inferred, but there was very little confidence for the location of the sighting (e.g., Alligator Creek was the only location stated, but there are multiple of them in Queensland)
Two	Only one general location could be found for the sighting (e.g. city, large river)
Three	Two general locations (e.g., city and large river), or one specific location (e.g., small creek) could be found for the sighting
Four	At least one precise location could be found for the sighting (e.g., building, street)

Sighting and Nesting Range Analysis

In order to determine changes in range over time, sightings and nests were divided across three time periods. The first represents the period preceding heavy crocodile exploitation (pre-exploitation; 1871-1944); the second covers the most intense years of crocodile hunting, post World War II (heavy exploitation; 1945-1971); the third represents the period after the embargo was placed on crocodile exports (post-exploitation; 1972-2015). Kernel density heat maps of the range of crocodile sightings and the range of crocodile nests were created in ArcGIS (ESRI 10.3). Sightings and nests were projected in WGS 84 / UTM Zone 55S using raster cell sizes of 3 km and 1.5 km, respectively. A search radius of 100 km was used for both sightings and nests, with the extents and masks set to a polygon of Queensland (Australian Bureau of Statistics 2011). The high/low heat-map scale was stretched separately across values for each time period, so that differences in crocodile abundance between time periods would not impair range comparisons within and between time periods.

Land Cover Analysis

In order to determine if land cover type affected the historical and modern spatial distribution of crocodiles, the number of sightings and nests on artificial land or cropland was determined as a percentage of total numbers of sightings and nests. First, a raster file of land cover data was obtained from the European Space Agency (2006). Raster cells were grouped into one of four categories: cropland, artificial land areas (i.e. urban area), water bodies and other (everything else, Appendix II). Crocodile sightings and nests were split into two time periods relative to heavy deforestation: pre-deforestation (until 1959) and post- deforestation (after 1960, McAlpine et al. 2009). Sightings and nests were then overlaid on the land cover data. Each sighting or nest was assigned a raster value, based on the land cover type upon which it fell. These data were then extracted from ArcGIS. Finally, the following value was calculated for each time period:

$$\frac{Number\ of\ sightings\ or\ nests\ on\ artificial\ land\ or\ cropland}{Total\ number\ of\ sightings\ and\ nests} * 100$$

This number was reported as a percentage and the percentages from both time periods were compared to one another. Differences between the two time periods in the frequencies of sightings and nests recorded on artificial land and cropland were tested for statistical significance with a chi-square test for independence by using function ‘chisq.test’ in the R package ‘MASS’ (R Core Team 2015).

Results

Sighting and Nesting Range

Sightings that represent the "most southern range" of crocodiles in Queensland through time shifted across the three time periods. This term refers to the southernmost area that is consistently inhabited. Today, the Queensland Government varies between designating the Boyne River (Queensland Parks and Wildlife Service 2007, Figure 2) and the Fitzroy River (about 75 km south of the Boyne, Queensland Government 2011, Figure 2) as the species' most southern range. However, in the pre-exploitation period, crocodiles were reported in the Mary River (about 225 km south of the Boyne, Figure 2) and in 1933, some considered the Mary River to represent the crocodiles' most southern range (Table 5). In the period of exploitation, this shifted to the north, as in 1953, citizens believed the Fitzroy River to be the most southern extent of crocodiles (Table 5). Citizens in 2015 were surprised to see crocodiles near the Mary River and believe that sightings could "signify a new trend" (Donaghey 2015). However, historical observations reveal that crocodiles were fairly high in abundance in the Mary River before 1890, and sighted sporadically in this river until 1953 (Table 5). Historical observations of crocodiles in the Mary River can be contrasted with those in the Fitzroy River, where, despite periods of lower sightings due to high hunting pressure, crocodiles were sighted consistently through time. Even in 2015, areas around the Fitzroy were considered to be "known crocodile habitat" (Table 6).

Table 5. Summary of key observations of crocodiles in the Mary River (Figure 2).

Year	Description
1890	Stories report this as a favorite crocodile area with many big crocodiles being shot and sighted.
1893	Article states that "it is nothing remarkable to discover a crocodile in the Mary River" and notes that an older resident said that crocodiles were once common here.
1904	Crocodiles of various sizes are sighted.
1917	Crocodiles are occasionally spotted in the river, but not very often.
1933	Article states that a crocodile was shot and that the Mary River represents the most southern range.
1936-1939	One crocodile is repeatedly seen by multiple people in Tiaro (south of the Mary River) and is eventually captured in 1939.
1947	Numerous crocodiles are sighted.
1951	Numerous crocodiles are sighted.
1953	Report of a crocodile killing a dog near the Mary River. It states that the Fitzroy River represents the most southern range and that this crocodile "may have lost its way" because the attack occurred 180 miles south of the Fitzroy.
2015	Article states that a crocodile was sighted in Tiaro, the "furthest south that the saltwater species has been spotted in recent history." It also states that this "could signify a new trend" as there have been three large crocodile sightings in recent years in the Mary River.

Table 6. Summary of key observations of crocodiles in the Fitzroy River (Figure 2).

Year	**Description**
1867	Article mentions that people hunt for crocodiles in the Fitzroy River.
1931	Many articles describe small crocodiles being caught.
1936	Fitzroy River was thought to be clear of crocodiles until a crocodile was caught. An article states that it is extremely unusual for a crocodile to be seen as far south as Rockhampton but prawners stated that it is not uncommon to find evidence of crocodiles in the river. There are still crocodiles that are hatching near the Fitzroy, suggesting that they are still ranging in the area and that these reported crocodiles are not strays.
1937	Numerous cattle attacks are reported near the Fitzroy River. Many articles describe hunting of crocodiles in the Fitzroy. A crocodile is reported close to the city of Rockhampton, which is considered unusual.
1938	Many articles state that crocodiles are being spotted in the Fitzroy. Fishermen believe that crocodiles are breeding in the area.
1939	There is an opinion among fishermen in the area that crocodiles are breeding at an island near the mouth of the river.
1940	Crocodiles are reported to be numerous in the upper reaches of the Fitzroy and a well-informed local believes that the banks are favorite breeding grounds. A resident finds a crocodile nest near the Fitzroy River.
1946	Fishermen that are working 80 miles up the river from Rockhampton report that crocodiles are more numerous than previously.
1948	Articles describe citizens shooting crocodiles in the Fitzroy. One says that crocodiles are numerous in the wintertime.
1952	Articles state that crocodiles may be increasing in the upper reaches of the Fitzroy
2015	The Fitzroy River is considered to be "known crocodile habitat."

While the location of the “most southern range” appears to have shifted, observations of individual crocodiles in southern Queensland have remained fairly consistent through time. Maps of crocodile sightings throughout Queensland reveal that, across all three time periods, individual crocodiles have been sighted as far south as

Maryborough and Brisbane (Figure 3). Individuals sighted sporadically in these southern areas were likely ‘nomadic’ males, which are known to continually travel throughout hundreds of kilometers of waterway (Campbell et al. 2013). The relative abundance of sightings in the southern areas has also remained fairly consistent through time, though the number and spatial extent of sightings near Brisbane is larger pre- and post-exploitation than during the heavy exploitation period (Figure 4). Low numbers of crocodiles have been sighted as far south as Brisbane (pre-exploitation = 4, heavy exploitation = 1, post-exploitation = 16). Slightly higher numbers have been sighted near Maryborough and Bundaberg across all time periods (pre-exploitation = 9, heavy exploitation = 11, post-exploitation = 46).

The size of individual crocodiles may help to illuminate whether individuals are ‘nomadic’ males, or representative of a local breeding population. During the pre-exploitation period, the average reported length of crocodiles seen south of Bundaberg was 3.9 meters (Table 7). Three crocodiles were over four meters in length and four crocodiles were four meters or less in length. During the heavy exploitation period, the mean reported length of crocodiles sighted south of Bundaberg was 2.4 meters. Two crocodiles were over four meters in length and eight crocodiles were under four meters in length. No size data were available for crocodiles sighted during the post-exploitation time period south of Bundaberg. These data suggest that prior to heavy exploitation, breeding populations likely existed in these southern areas, whereas during heavy exploitation, they were depleted.

The geographic center of the crocodile range does not appear to have shifted either, with the highest concentration areas occurring from above Port Douglas to below Townsville, as well as near Mackay and Rockhampton (Figure 4). Relatively higher concentrations in Maryborough during the heavy exploitation period likely reflect a lower number of observations in this time period (Figure 3b, 4b). During the post-exploitation period, a relatively high proportion of crocodile sightings was also recorded near Cooktown and at lower latitude near the tip of Queensland, which may reflect range extension, or survey effort. In particular, the fact that the highest numbers of sightings occur near urban areas suggests that observational effort likely has a substantial influence on the concentrations shown.

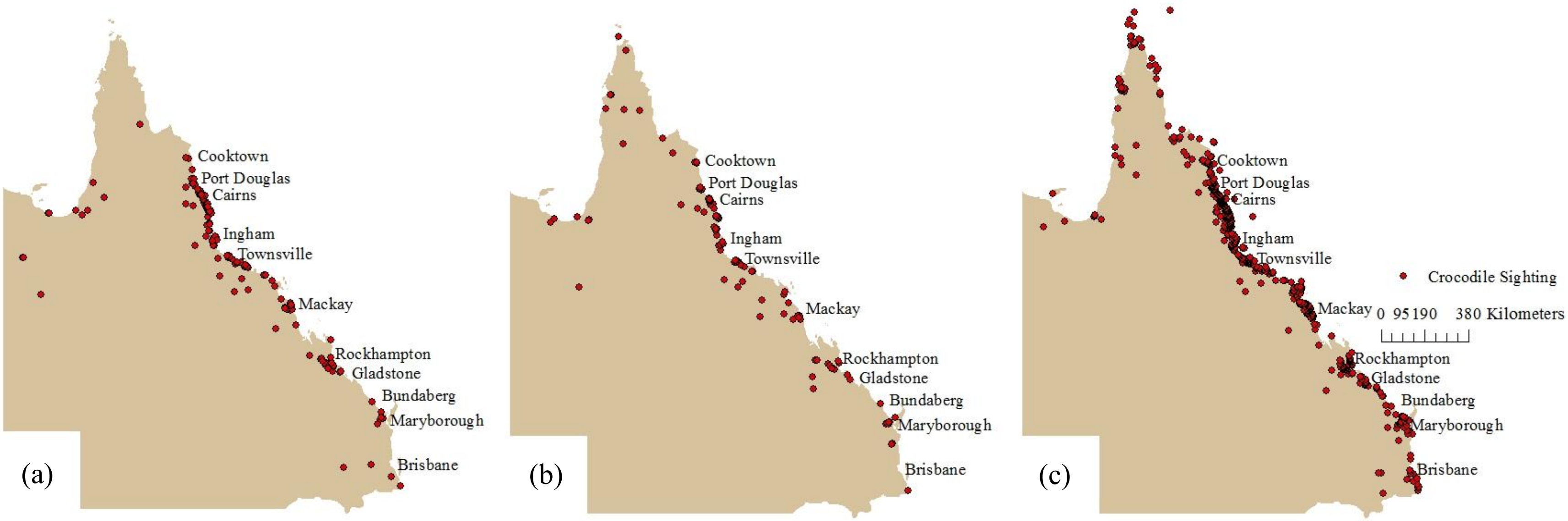

Figure 3. Crocodile sightings with comparatively high location certainties through time relative to period of heavy crocodile exploitation: (a) pre-exploitation (1871-1944), (b) heavy exploitation (1945-1971), and (c) post-exploitation (1972-2015). Sightings data were extracted from Trove (National Library of Australia 2015), CrocWatch (Department of Environment and Heritage Protection 2016) and CrocBITE (CrocBITE 2016).

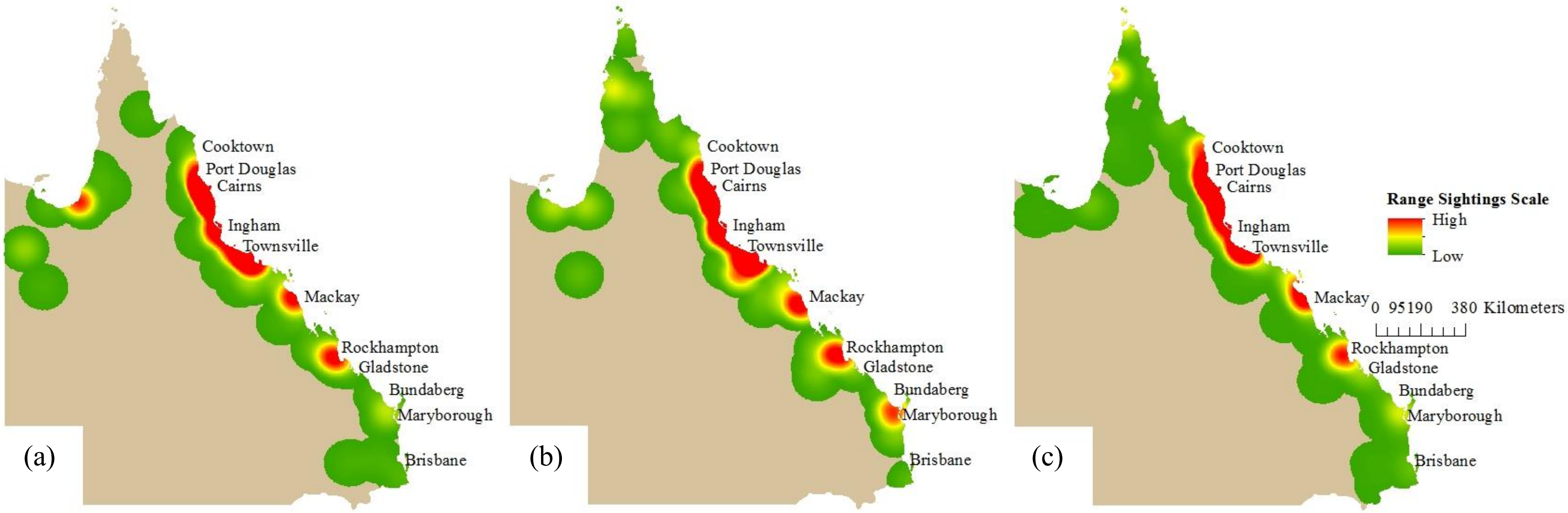

Figure 4. Heat maps of crocodile sightings with comparatively high location certainties through time relative to period of heavy crocodile exploitation: (a) pre-exploitation (1871-1944), (b) heavy exploitation (1945-1971), and (c) post-exploitation (1972-2015). The scale of sightings is constructed separately for each time period to facilitate comparison of spatial distribution regardless of temporal differences in number of sightings reported. Sighting data were extracted from Trove (National Library of Australia 2015), CrocWatch (Department of Environment and Heritage Protection 2016) and CrocBITE (CrocBITE 2016).

Table 7. The size of crocodiles (m) observed south of Bundaberg during pre-exploitation and heavy exploitation time periods. No size data were available for crocodiles in this areas sighted in the post-exploitation period.

Time Period	> 4 m	≤ 4 m	Average Length (m)
Pre-exploitation	3 (4.5, 4.6, 6)	4 (1.5, 2.7, 3.8, 4.0)	3.9
Heavy exploitation	2 (4.3, 4.3)	8 (1.2, 1.2, 1.2, 1.8, 1.8, 2.4, 2.4, 3.4)	2.4

Finally, crocodile nesting ranges may have contracted through time, although this is difficult to characterize due to limited data. Around 1940, crocodiles were believed to be breeding near the mouth of the Fitzroy River, and a nest was found near the upper reaches of the river (Table 6). However, the data used did not reveal nests below Mackay (about 310 km north of the Fitzroy) in the period of heavy exploitation or in the post-exploitation period (Figure 5). Spotlight surveys conducted from 1998 to 1999 discovered hatchlings in the remote regions of the Fitzroy, although these sightings were not included in analysis as researchers were actively seeking crocodiles (Read 1999).

A relatively high proportion of nests have continued to be recorded near Port Douglas, Cairns and Mackay, but nests appear to be patchier in distribution in comparison to historical sightings, which were more continuous along Queensland’s coastline (Figure 6). Although CrocWatch represents the largest source of data for this study (1,733 sightings), only five nests were reported over the six-year period (2010-2015), four of which had precise enough location certainties to include in this analysis. In contrast, only 556 sightings come from Trove (1871-1957), but 26 nests were reported during that earlier period (Figure 5). While the Trove data do represent a much wider timeframe, human population was lower than it is it at present, so overall survey effort within those years was lower as well. Thus, valid comparisons between the two time periods should account for possible bias related to differences in human population size and number of years covered by each time period.

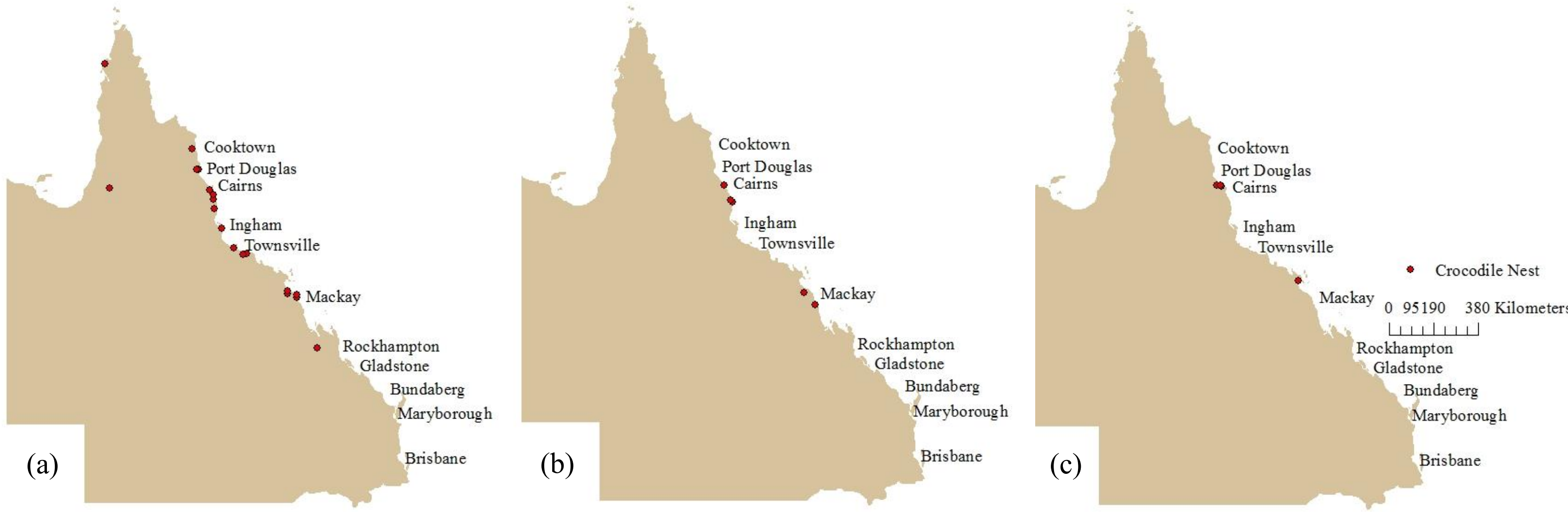

Figure 5. Crocodile nests with comparatively high location certainties through time relative to the period of heavy crocodile exploitation: (a) pre-exploitation (1871-1944), (b) heavy exploitation (1945-1971), and (c) post-exploitation (1972-2015). Nesting data were extracted from Trove (National Library of Australia 2015) and CrocWatch (Department of Environment and Heritage Protection 2016).

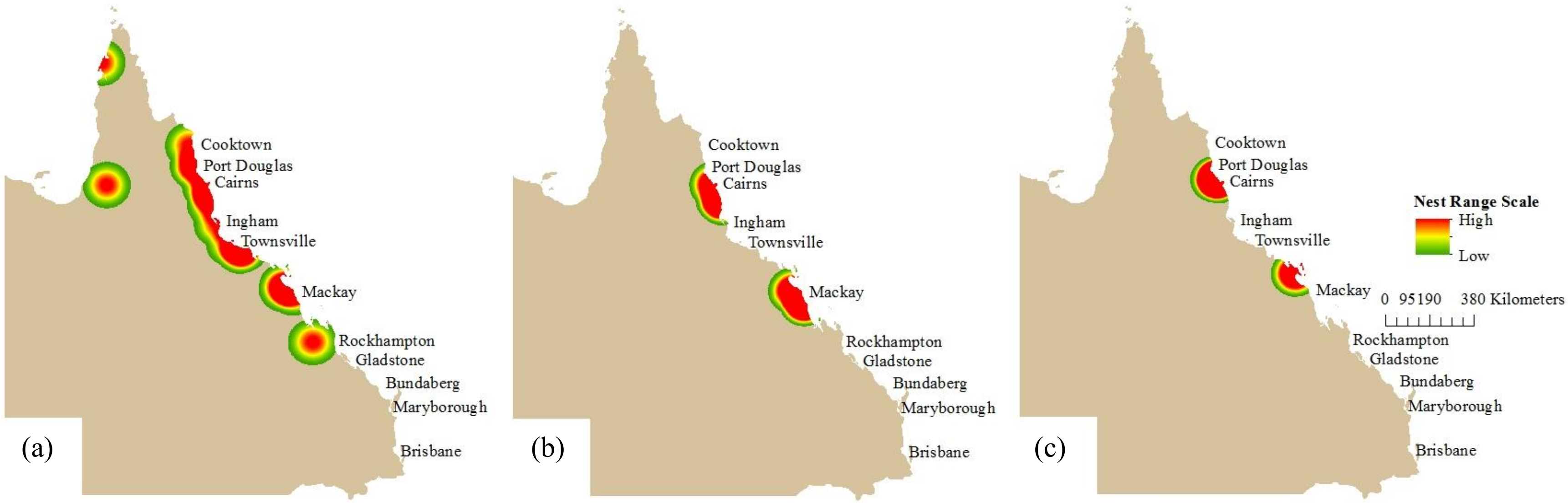

Figure 6. Heat maps of crocodile nests with comparatively high location certainties through time relative to the period of heavy crocodile exploitation: (a) pre-exploitation (1871-1944), (b) heavy exploitation (1945-1971), and (c) post-exploitation (1972-2015). The scale is constructed separately for each time period to facilitate comparison of spatial distribution of nests regardless of temporal differences in numbers reported. Nesting data were extracted from Trove (National Library of Australia 2015) and CrocWatch (Department of Environment and Heritage Protection 2016).

Range Relative to Land Cover

Over the past 50 years, Queensland has experienced heavy land clearing (McAlpine et al. 2009). The data in this study suggest that crocodiles have overlapped with these human-altered areas over time. There was no statistically significant difference between the percentage of crocodile or crocodile nest sightings before 1960 (1871-1959, 19.4%) that fell on land that was cropland or artificial land areas in 2004 – 2006 in comparison to crocodile sightings and nests that were observed in these areas after 1960 (16.9%, χ^2 = 1.42, df = 1, P = 0.23).

As most sightings and nests occur along Queensland's coastline, where the majority of cropland and urban areas are located, there has likely been substantial crocodile habitat destruction and human-crocodile interaction (Figure 7). The agricultural development occurring across the state is reducing the available remaining habitat for crocodiles and may be driving individuals into these urban areas.

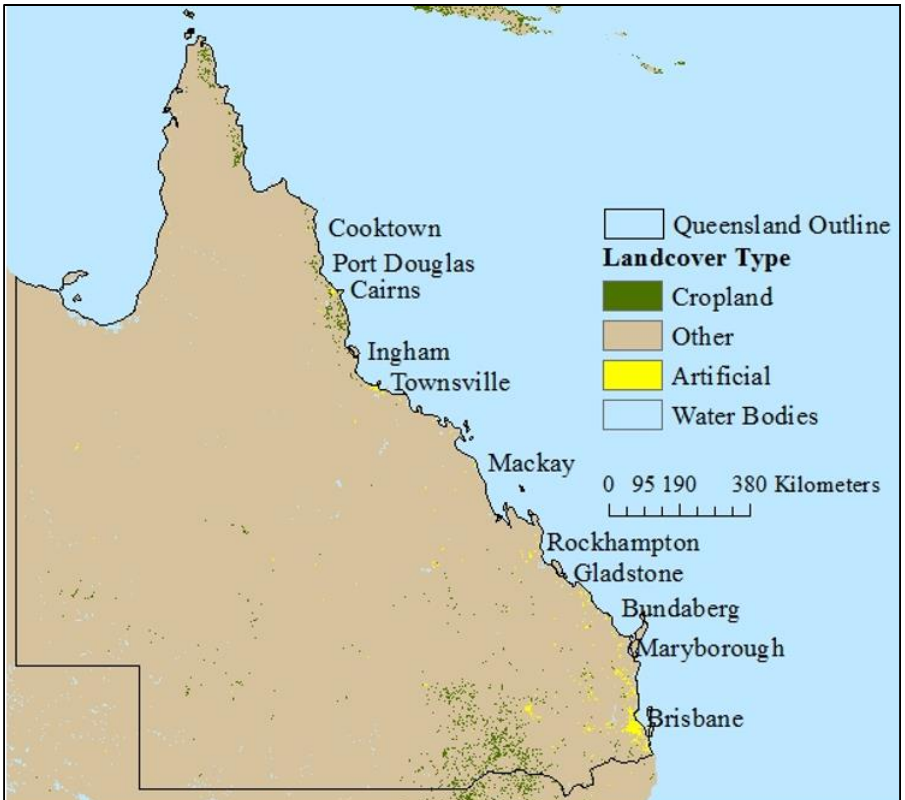

Figure 7. Human-altered land cover in Queensland, Australia. The land cover raster file was taken from the European Space Agency (2009).

CHAPTER THREE: ABUNDANCE

Hypothesis: Crocodile populations have recovered to historical baseline abundances in areas that abut regions of high human population density.

Methods

To estimate relative abundance over time, the number of crocodile sightings data described in Chapter Two was standardized by human population size over time to account for density-dependent reporting bias. Human population influences the effort involved in sighting crocodiles, and it is therefore important to factor it into spatial and temporal analyses of crocodile abundance estimated from observations alone. To make use of the most complete historical data on human population size, analyses were limited by proximity to city centers. The largest cities in Queensland were chosen based on current human population, location and available census data, with the selected cities being, in order from low to high latitude: Cooktown (pop. 2,339), Port Douglas (pop. 3,205), Carins (pop. 133,893), Ingham (pop. 4,767), Townville (pop. 157,748), Mackay (pop. 77,293), Rockhampton (pop. 61,724), Gladstone (pop. 32,073), Bundaberg (pop. 49,750), Maryborough (pop. 21,777) and Brisbane (pop. 1,977,315) (Centre for the Government of Queensland 2011). The center of each city was obtained from LatLong.net (2016). A 25-kilometer buffer was created around each city center using ArcGIS (ESRI 10.3). This buffer size was chosen because it was the largest extent that did not allow cities to overlap. Only sightings that intersected with these buffered areas were kept on the map and were assigned their respective city name.

Census data for each city through time were taken from the Centre for the Government of Queensland (2011). The “approx” function in package ‘stats’ (R Core Team 2015) was used to interpolate human population for each year in which a sighting occurred, based on the available census data for the respective city. Data were limited to the years of 1871 through 2011 as these years represent the outer limits of available census data, though a few sightings had to be excluded because the associated cities did not have census data as early as the sightings occurred.

A linear response was assumed between human population size and number of crocodile sightings (Herrero et al. 2011). To map sightings, sightings were normalized by interpolated human population by first grouping the data by the city and year. The mean interpolated human population and sum of the sightings were both summarized using the package ‘dplyr’ (R Core Team 2015). The data were then grouped by city and the following equation, in which “sightings” refers to the summarized sum of sightings and “interpolated human population” refers to the summarized mean interpolated human population, was used to find the normalized sighting value for each city:

$$\frac{\left(\frac{sum(sightings)}{sum(interpolated\ human\ population)} * 10{,}000\right)}{Number\ of\ years\ with\ sightings\ during\ the\ time\ period}$$

The number of years in which crocodile sightings occurred within each time period was used to normalize the data, as opposed to the range of years within each time period, because effort was not constant throughout each time period due to data gaps.

The value of the normalized sightings within each city was mapped for three time periods: pre-exploitation (1871-1944), heavy exploitation (1945-1971), and post-exploitation (1972-2015). They were projected in WGS 84 / UTM Zone 55S. The scale was manually classified to be identical for all three time periods so that the normalized sighting value within each city could be directly compared between time periods.

To visualize normalized sighting through time, sightings were again normalized by interpolated human population by first grouping the data by the city and year. The mean interpolated human population and sum of the sightings were both calculated using the package ‘dplyr’ (R Core Team 2015). The normalized sighting value for each year was determined with the following equation:

$$\frac{sum(sightings)}{sum(interpolated\ human\ population)} * 10{,}000$$

where “sightings” is the sum of sightings and “interpolated human population” is the mean interpolated human population. The normalized sighting value for each year was plotted using R package ‘ggplot2’ (R Core Team 2015). A robust LOESS curve (span = 1, degree = 1) was used to show the smoothed trend of the data over time. Additionally, the total number of the modern sightings for each year was plotted from 2010 through 2015 using ‘ggplot2’ with a robust LOESS (span = 1, degree = 1) to show how crocodile sightings have changed over the past six years. Finally, human population, faceted by city, was plotted through time using ‘ggplot2’ as well.

Results

Over the past 150 years, human populations have increased in many cities across Queensland, with the most dramatic increase occurring in Brisbane (Figure 8). Cairns, Townsville, Mackay and Rockhampton also have experienced substantial human population increases through time. In contrast, a few northern cities, such as Cooktown, Port Douglas and Ingham, have changed relatively little in population size.

Normalized crocodile sightings display a slight negative trend throughout the pre-exploitation period and then remain relatively constant through the heavy exploitation period and post-exploitation period (Figure 9). The high pre-exploitation points are likely due to relatively low human population sizes in the years and locations in which those sightings took place. This preliminary analysis suggests that crocodile sightings from Trove, CrocWatch and CrocBITE do not seem to serve as accurate proxies for crocodile abundance through time due to inconsistent sighting effort. In particular, it appears that data gaps exist in the 1860s and 1910s and between 1960 and 2000 (Table 8). The data gaps that exist are highly apparent when the number of sightings included in these analyses is divided by decade (Table 8). As well, Trove, CrocWatch and CrocBITE all vary substantially in the nature of their reporting, and as CrocBITE is the only source to represent comprehensive data, this deficit renders characterizing crocodile abundance from these sources extremely difficult.

Despite the current inability to quantify abundance change over time, historical observations of crocodiles at high concentrations suggest that they were once in high abundance (Table 9). High numbers of crocodiles were hunted in northern Queensland (Figure 10) prior to the federal embargo placed on crocodile exports in 1972 and there was great determination among citizens to heavily exploit crocodiles. Some hunters even reported wanting to exterminate the species.

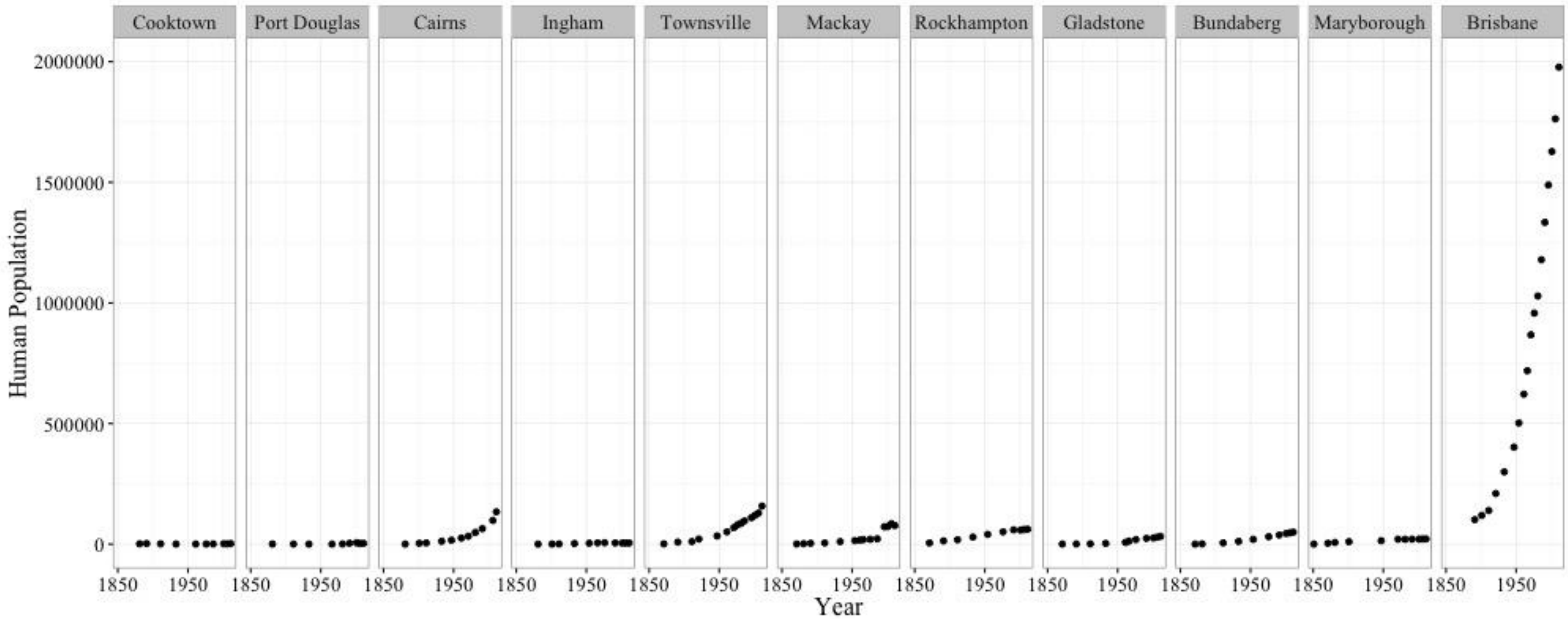

Figure 8. Human population census data for major cities in Queensland through time (Centre for the Government of Queensland 2011). Cities are listed from left to right in order from low to high latitude.

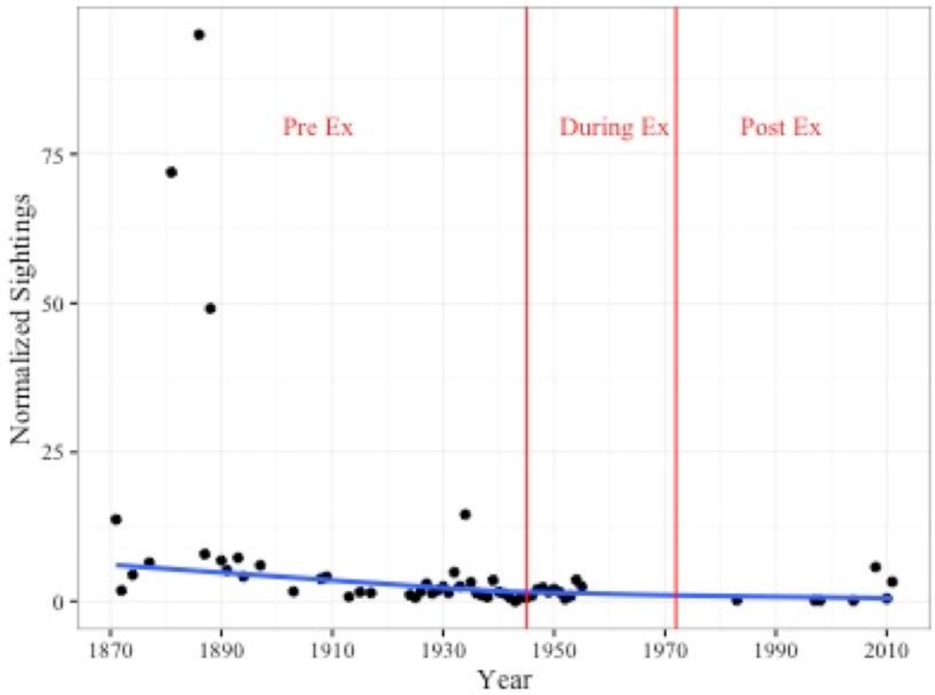

Figure 9. The number of crocodiles sighted in the urban centers of Queensland over time, normalized by human population (per 10,000 people). Each vertical line splits the data by time period and the curve represents the robust LOESS fit (span = 1, degree = 1), which shows the smoothed trend over time.

Table 8. The number of crocodiles sightings in each decade included in analyses. Data gaps are bolded.

Decade	Number of Crocodile Sightings Included in Analysis
1860	**2**
1870	10
1880	11
1890	14
1900	31
1910	**6**
1920	59
1930	202
1940	131
1950	111
1960	**0**
1970	**1**
1980	**4**
1990	**4**
2000	11
2010	1643

Table 9. Instances of high crocodile hunting pressure (≥20 crocodiles) in Queensland.

Year	**Hunting Location**	**Number of Crocodiles**	**Description**
1938	Gulf of Carpentaria	100	A man kills about 100 crocodiles over two months in the Gulf of Carpentaria.
1947	Gulf of Carpentaria	100	A retired police officer returns home after shooting 100 crocodiles in six weeks.
1950	North Queensland	73	A party of crocodile shooters in the Peninsula bags 73 crocodiles.
1950	Flinders and Gilbert River	40	During a shooting expedition about 40 crocodile skins are obtained.
1951	Princess Charlotte Bay	150	A man returns after a 12-week crocodile hunting expedition with 150 skins.
1951	Unknown	106	A young crocodile hunter returns to Cooktown with 106 skins.
1952	Laura	40	A police officer states that he shot 40 crocodiles in one night and up to 400 in one year.
1953	Karumba	3000-4000	The president of the Australian Crocodile Shooters' club states that there are about 3000 to 4000 crocodile to be shot in the area. Using a spotlight, he sighted 40 crocodiles in a creek in one night.
1953	Cape York	300	A professional crocodile shooter returns home with 300 skins and claims that there are still plenty of crocodiles.
1953	Normanby River	40	A group of men shoot 40 crocodiles.
1953	Gulf of Carpentaria	25	The Australian Crocodile Shooters Club "aims to exterminate crocodiles from Gulf rivers." They average about 25 kills each week.
1954	Cape York	28	Seven crocodile shooters bag 28 crocodile skins on a hunting expedition.

Likewise, mapped sightings within urban areas of Queensland appear to be an imperfect proxy of abundance over time, as pre-exploitation crocodile populations appear lower in abundance than during exploitation or post-exploitation (Figure 11). These findings contrast results from the temporal graph in which sightings decrease through time, which may be attributed to differences in the normalization technique for each analysis. For example, the high normalized sightings rates in Port Douglas during the heavy exploitation period and post-exploitation period are likely partially attributed to the low human population in this city through time, in comparison to cities farther south, such as Townsville and Brisbane. Sightings appear geographically consistent, as, across all maps, crocodiles are sighted in the highest density in Port Douglas. Cooktown also has relatively high densities of crocodile sightings in all three time periods. The more southern cities display lower crocodile abundances than the northern cities during all three time periods. In the post-exploitative period, there appear to be more sightings from Ingham to Mackay than in the previous time periods

Figure 10. Locations of instances of high crocodile hunting pressure (>20 crocodiles) in Queensland (ESRI 2013, Department of Natural Resources and Mines 2014).

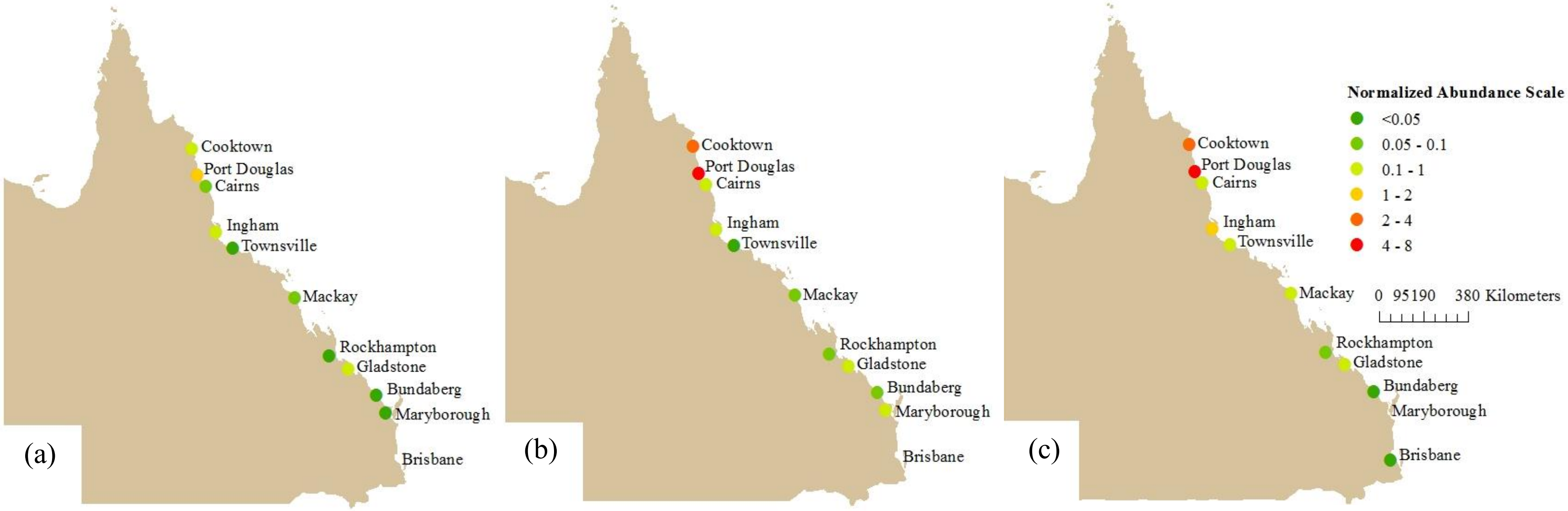

Figure 11. Heat maps of normalized crocodile sightings with comparatively high location certainties in urban centers of Queensland through time relative to the period of heavy crocodile exploitation: (a) pre-exploitation (1871-1944), (b) heavy exploitation (1945-1971), and (c) post-exploitation (1972-2015). The scale is manually classified to use the same range of values for each time period so that sighting rates can be compared directly across both time and space. Sightings data were extracted from Trove (National Library of Australia 2015), CrocWatch (Department of Environment and Heritage Protection 2016) and CrocBITE (CrocBITE 2016), and were normalized by human population (per 10,000 people; Centre for the Government of Queensland 2011) and the number of years in which sightings occurred during the time period.

While the disparate nature of the sources makes it difficult to examine long-term changes in crocodile abundance, consistent data during the past six years reveal only a slight upward trend in crocodile sightings. Confirmed and unconfirmed sightings from CrocWatch, combined with attacks from CrocBITE, show that sightings increased between 2010 and 2012, then decreased from 2012 to 2014, and increased again in 2015 (Figure 12). It is possible that low numbers of sightings in 2010 may be attributed to the novelty of CrocWatch, as this is the year in which it began. The total number of sightings is highly variable from year to year and, consequently, these data do not indicate a recent upward trend in crocodile abundance.

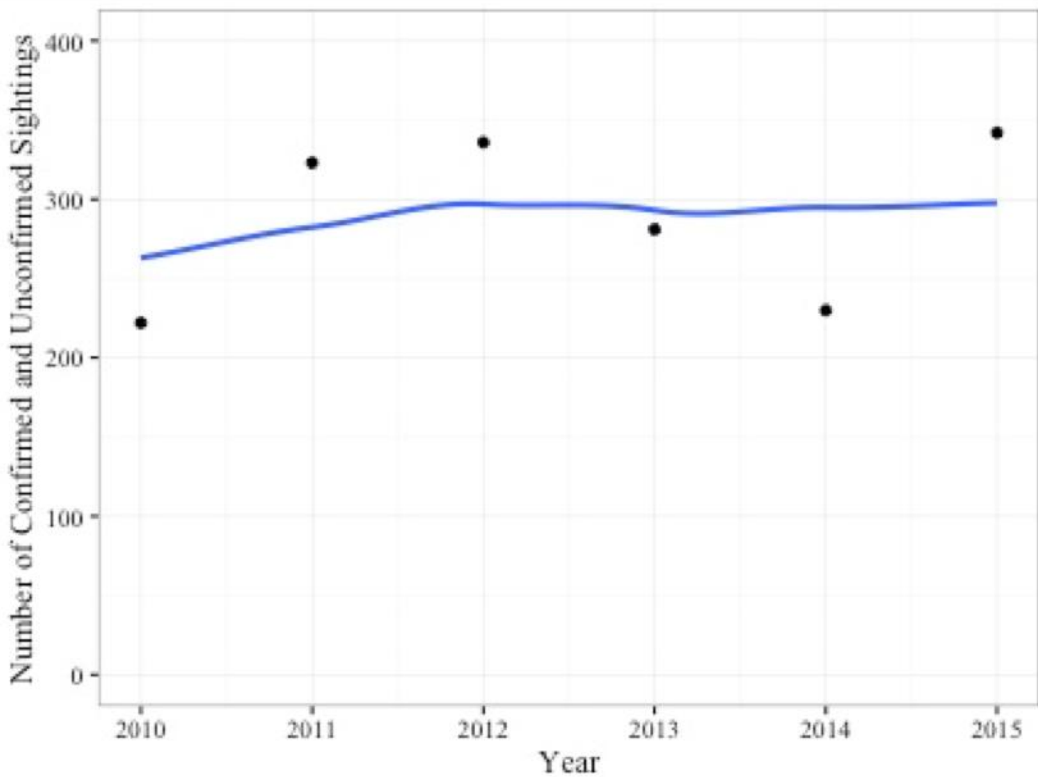

Figure 12. The total number of crocodile sightings across Queensland from 2010 through 2015. The curve represents the robust LOESS fit (span = 1, degree = 1), which shows the smoothed trend over time.

CHAPTER FOUR: HUMAN-WILDLIFE CONFLICT

Hypothesis: Crocodile attack rates have increased over time relative to human population size.

Methods

The crocodile sightings data were again limited by the 25-kilometer buffer around city centers, and were further restricted to sightings that pertained to either a fatal or non-fatal attack on a human. A linear response was assumed between human population size and crocodile attacks. To map attacks, attacks were normalized by interpolated human population by first grouping the data by the city and year. The mean interpolated human population and sum of the attacks were both calculated using the package 'dplyr' (R Core Team 2015). For each city, the normalized sighting value was determined using the following equation:

$$\frac{\left(\frac{sum(attacks)}{sum(interpolated\ human\ population)} * 10{,}000\right)}{Range\ of\ years\ in\ the\ time\ period}$$

where "attacks" is the sum of attacks and "interpolated human population" is the mean interpolated human population. As opposed to sightings data, which are opportunistic, it was assumed that reported attacks were comprehensive, as the media reports most crocodile attacks. Therefore, the reporting effort was treated as constant and the entire range of years in the time period was used to normalize the sightings. This method differs from that used in Chapter Three, which normalized the number of sightings using only the years in which crocodiles were sighted.

The value of the normalized sightings within each city was mapped for three time periods: pre-exploitation (1871-1944), heavy exploitation (1945-1971), and post-exploitation (1972-2015). They were projected in WGS 84 / UTM Zone 55S. The scale was manually classified to be identical for all three time periods so that the normalized attack value within each city could be directly compared between time periods.

To visualize normalized sighting through time, attacks were again normalized by interpolated human population by first grouping the data by the city and year. The mean interpolated human population and sum of the attacks were both summarized using the package ‘dplyr’ (R Core Team 2015). The data were then grouped by decade and the following equation, in which “attacks” refers to the summarized sum of sightings and “interpolated human population” refers to the summarized mean interpolated human population, was used to find the normalized sighting value for each decade:

$$\frac{sum(sightings)}{sum(interpolated\ human\ population)} * 10{,}000$$

The normalized sighting value for each decade was plotted through time and a robust LOESS curve (span = 1, degree = 1), was fit to the data to show the overall smoothed trend. The raw numbers of attacks (not normalized) were plotted by decade as well and a robust LOESS curve (span = 1, degree = 1) were fit to these data. As the data were treated as continuous for both of these graphs, zeros were added during decades in which no attacks occurred.

Results

Since the 1870s, approximately 91 crocodile attacks have occurred across Queensland. At least one human has been attacked by a crocodile during every decade, except in the 1960s during which no attacks occurred. There is a trend of higher numbers of total crocodile attacks occurring throughout Queensland prior to heavy exploitation than during the post-exploitation time period (Figure 13). There appears to be a spike in attacks during the decade of 2000, but this is substantially lower than the number of attacks in the decade of 1930 and similar to the number of attacks that occurred in the decades of 1940 and 1950 as well (Figure 13). Overall, attack rates appear to have remained relatively low during the post-exploitation period.

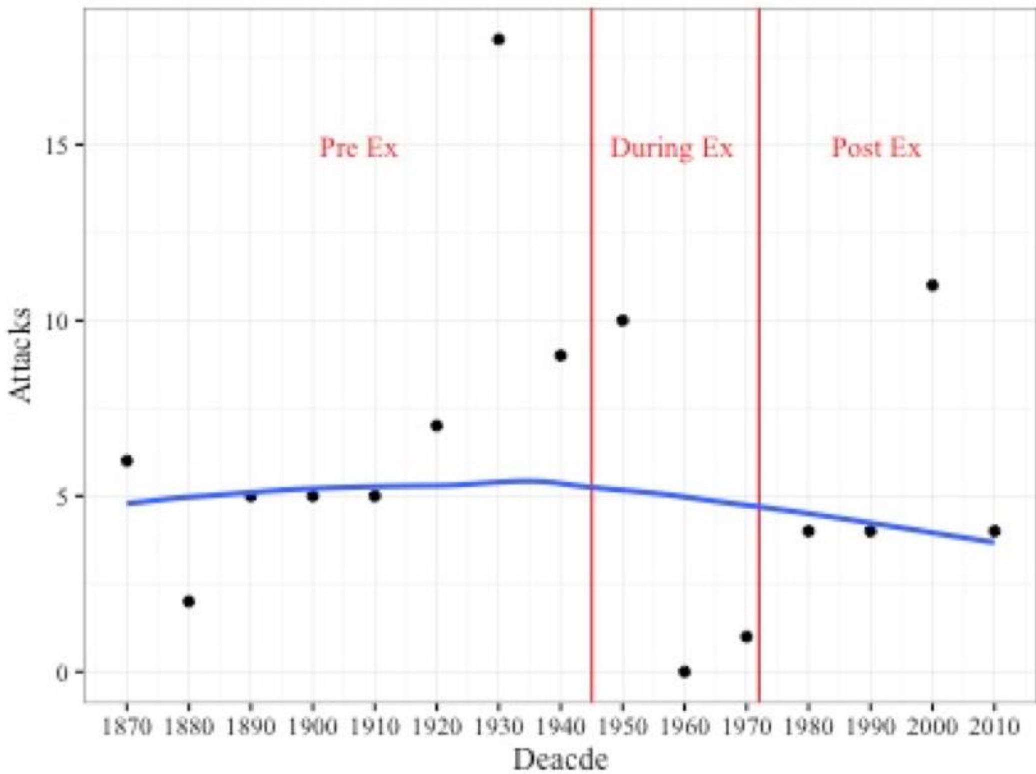

Figure 13. The distribution of the raw number of attacks occurring in each decade since 1870. Each vertical line splits the data by time period and the curve represents the robust LOESS fit (span = 1, degree = 1), which shows the smoothed trend over time.

Normalized data further suggest that crocodile attack rates are lower in the post-exploitation period than they were in the pre-exploitation period. An overall trend of decreasing normalized attack rate since 1871 is apparent and there is an extreme outlier in 1880 when the normalized attack rate was extremely high (Figure 14). This outlier likely stems from low interpolated human population associated with the two cities (Cairns = 278 people and Ingham = 105 people) in which the sightings took place relative to sightings in other decades. Few attacks occurred during the heavy exploitation period, which could explain why some citizens believe that limiting crocodile recovery will reduce attack rates on humans. However, normalized attack rates do not appear to have increased since the heavy exploitation period and remain substantially lower in comparison to the pre-exploitation period.

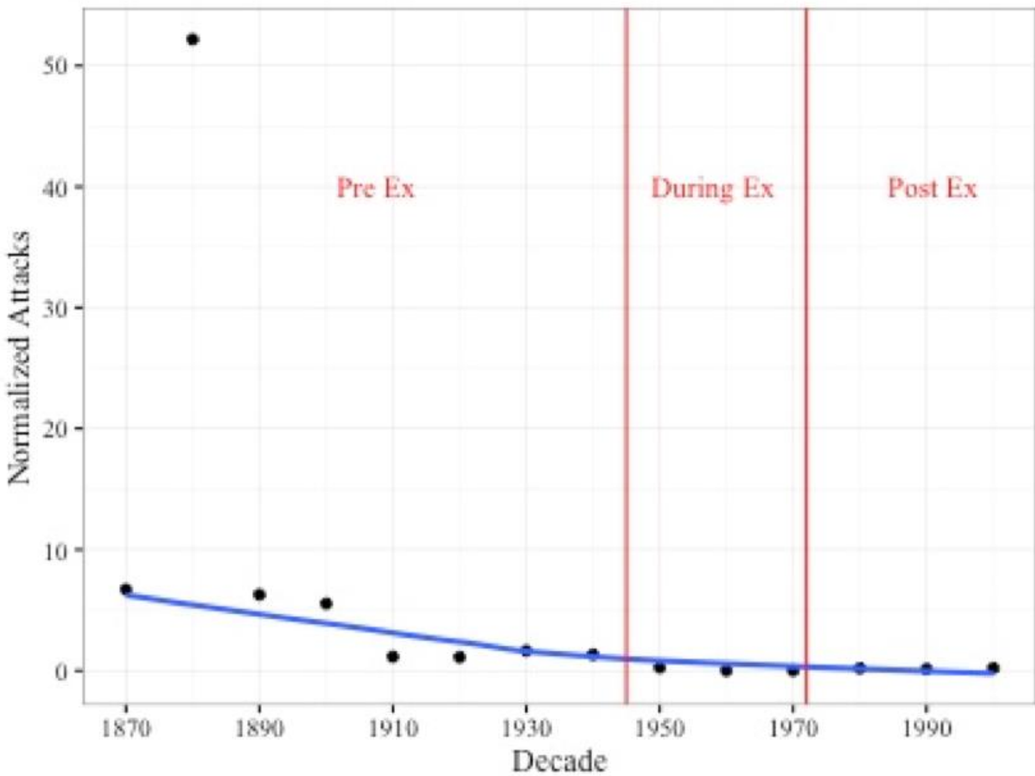

Figure 14. The number of crocodile attacks occurring in the urban centers of Queensland over time, normalized by human population (per 10,000 people). Each vertical line splits the data by time period and the curve represents the robust LOESS fit (span = 1, degree = 1), which shows the smoothed trend over time.

Maps of urban sightings through time again display this trend in which crocodile attack rates are relatively high prior to heavy exploitation, decline during the heavy exploitation period, and increase slightly in intensity during post-exploitation (Figure 15). Attacks appear to be geographically restricted to Cooktown and Cairns during the post-exploitation period. In the heavy exploitation period, they occur in Cairns and in Townsville. During the pre-exploitation period, they occur in high density in Port Douglas, in moderate density in Cooktown, Ingham, Townsville, Mackay and Gladstone, and in low density in Maryborough. However, during the heavy exploitation and post-exploitation periods, no sightings occur in Port Douglas, which is particularly important because this city represented the highest normalized sighting value (Figure 11).

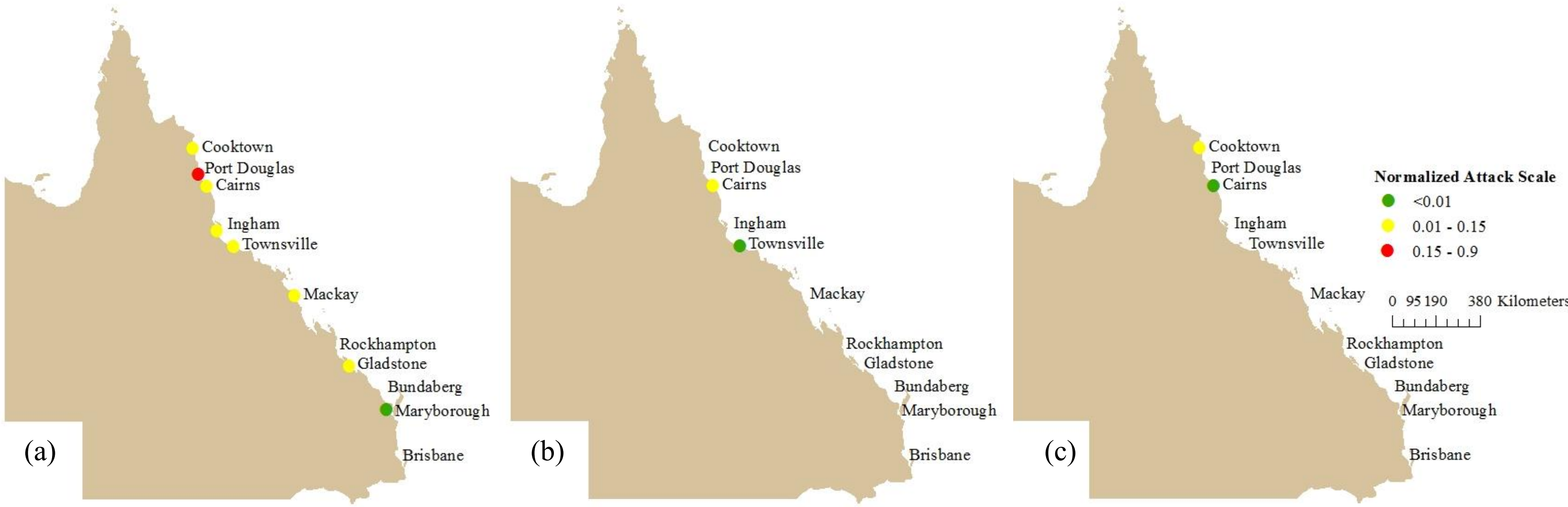

Figure 15. The grouped value of normalized crocodile attacks with relatively high location certainties within urban cities of Queensland through time. Attack data were extracted from Trove (National Library of Australia 2015) and CrocBITE (CrocBITE 2016), and were normalized by human population (Centre for the Government of Queensland 2011) and the range of years in each respective time period. The scale is manually classified to follow the same range of values for each time period. (a) Pre heavy crocodile exploitation (1871-1944). (b) Heavy crocodile exploitation (1945-1971). (c) Post heavy crocodile exploitation (1972-2011).

CHAPTER FIVE: DISCUSSION

Range

In recent years, citizens have been surprised to spot crocodiles as far south as Brisbane (Donaghey 2015). This could indicate a "shifting baseline syndrome" (Pauly 1995) in which citizens believe crocodile ranges to be expanding when, in reality, they are recolonizing areas in which heavy hunting pressure had led to their local extirpation. In order to study the range of crocodiles, understanding their behavior is crucial. Male crocodiles can either be 'site-fidelic' (mean size 4.1 m), moving only within zones around female home ranges or 'nomadic' (mean size 3.8 m), moving continually within hundreds of kilometers of waterway. Female crocodiles are often smaller than both 'site-fidelic' and 'nomadic' males (Campbell et al. 2013). Thus, the range of crocodiles can be described by at least three parameters: locations of 'site-fidelic' males, locations of 'nomadic' males and finally, locations of females and nests.

Anecdotal evidence suggests that during the pre-exploitation period, crocodiles were continually sighted throughout southern Queensland (south of Bundaberg), and some were sighted during the heavy exploitation period as well. Crocodiles over 4.1 meters in length were sighted during both of these time periods, suggesting the presence of 'site-fidelic' males. During the two most recent crocodile abundance surveys conducted during 2007 and 2009/2010, however, researchers found no evidence to suggest that crocodile range includes areas south of the Boyne River (near Rockhampton) or south of the Fitzroy River (Queensland Parks and Wildlife Service 2007, Queensland Government 2011). This finding may suggest that crocodiles have been in lower numbers in these southern areas following the heavy exploitation period. Thus, in recent years, when crocodiles have been spotted in areas south of the Boyne River, citizens have been surprised by their presence (Donaghey 2015). Though the large individuals sighted in the pre-exploitation time period suggest that these areas represent historical ranges, crocodiles spotted south of the Boyne in recent years have often been closer to 3.6 m in length, which may indicate that they are 'nomadic' males (Queensland Government 2013).

The question of drivers of range expansion remains open, with climate change suggested as a possible driver of expansion south (Donaghey 2015). However, spatial analysis of the nesting data indicates that prior to the heavy exploitation period crocodile nests were spotted by citizens farther south than they have been during the post-exploitation period, which may suggest that crocodiles are simply re-expanding into historical range, rather than responding to warmer temperatures. During the 2009/2010 government survey, about 37 percent of waterways that were surveyed north of the Boyne River included hatchlings. No hatchlings were spotted in the Boyne River or the Mary River, but one hatchling was observed in the Fitzroy River (Queensland Government 2011). Thus, the presence of crocodile hatchlings along Queensland's coast, as described by these surveys, suggests that nesting range likely has not contracted vertically. However, the low number of nests reported by citizens in recent years may indicate that nesting areas are shifting out of anthropogenically altered areas and, thus, humans are not observing them as frequently.

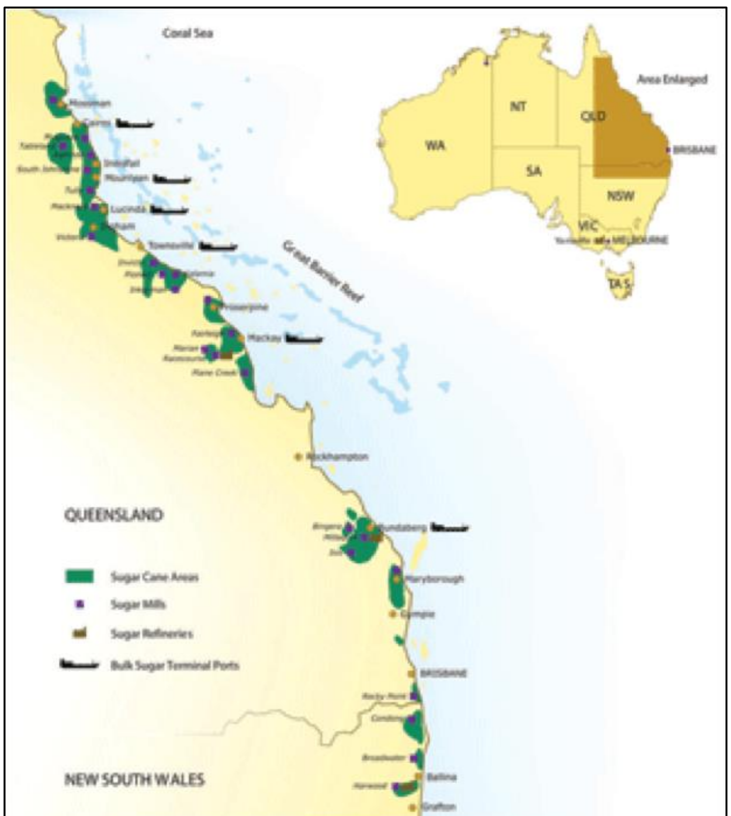

Figure 16. Production of sugar cane along Queensland's coastline (Canegrowers 2010).

Habitat alteration has likely affected the breeding behavior of crocodiles, as evidenced by the low numbers of nests reported by citizens in recent years. Although the percentage of crocodiles sighted on what is currently cropland and artificial substrates associated with urbanization did not change significantly from the percentage that was recorded there before heavy habitat modification took place, the substantial spatial overlap between the location of this anthropogenically altered land and all crocodile sightings suggests the potential for negative effects of habitat alteration on the species. For example, areas of sugar cane production occur along the coast of Queensland (Canegrowers 2010, Figure 16), coincident with many historical crocodile sightings. Importantly, few sightings of nests have been reported during the post-exploitation period, and the few that have been reported exhibited pronounced contraction to two small coastal areas. This finding suggests that increased human development and habitat alteration may be driving nesting out of areas in which humans commonly spot them. For example, human habitat alteration, such as beef cattle grazing, has been shown to destroy crocodile nests, which further supports this theory (Taplin 1987).

Abundance

Reliable information about trends in crocodile abundance through time do not currently exist (Grigg and Kirshner 2015). While this study aimed to glean some sense of temporal crocodile numbers, the data collected were not able to address this issue directly, and seem to offer contradictory insights into long-term patterns. For example, while sightings maps show an increasing trend in normalized sightings in urban areas from the pre-exploitation period to the post-exploitation period, graphing the data by year reveal that a slight decline in normalized sightings has occurred since the pre-exploitation period. Anecdotal evidence supports the declining trend in sightings through time by suggesting that crocodile sightings were once much higher in Queensland than they are at present. For example, numerous pilots who flew over Australia's northern beaches in the early 1940s reported seeing "scores" of large crocodiles (Grigg and Kirshner 2015) and there are no recent sightings of such magnitude. However, gaps in the data and varying survey effort make it difficult to discern the validity of these trends. For example, CrocWatch, the current citizen science reporting system, represents a much more complete set of sightings than reports of sightings in historical newspapers. The unreliable nature of public sightings data is further substantiated by the 2009/2010 crocodile survey report, which claims that it "should not be used as a basis for interpreting population structure and dynamics" (Queensland Government 2011).

Data from continuous sightings effort over the past six years reveal that crocodile sightings have only displayed a slight increasing trend. However, this may be due to variable observational effort as citizens were first familiarizing themselves with CrocWatch. While the Courier Mail reported a 20 percent spike in unconfirmed sightings between 2010 and 2014 (Donaghey 2015), analysis from this study found the spike to be closer to 13 percent. Additionally, when combined with confirmed sightings as well, the trend of crocodile sightings between 2010 and 2015 do not display a substantial incline. Thus, newspaper reporting may be causing misguided opinions about crocodile abundance among citizens.

Historical hunting anecdotes reveal that crocodiles were once sighted and killed in high density in northern Queensland. These anecdotes suggest very high pre-exploitation abundance, and reveal the heavy exploitation that took place following the Second World War. The 2009/2010 crocodile abundance survey found no evidence of a significant increase in crocodiles along Queensland's populated coast (Queensland Government 2011), suggesting that crocodile populations still remain low relative to pre-exploitation periods. Due to patchy nesting habitat areas, active removal of crocodiles, and human population and land use expansion, experts believe that crocodiles will remain in lower numbers south of Port Douglas (Grigg and Kirshner 2015). Across Queensland's coastline, human populations have been expanding, which is likely representing the driving force behind the slow crocodile recovery in the state.

Human-Wildlife Conflict

Many activities, such as wading and splashing at the edge of crocodile-infested waters, can lead to crocodile attacks (Grigg and Kirshner 2015). Fukuda et al. (2015) suggested that participating in any activity involving swimming in an area not deemed "safe" by management poses an unacceptable risk. Despite increases in human population along Queensland's coast, the results suggest that attacks have remained relatively low in comparison to pre-exploitation times. Observing raw attacks through time, which still display a slight decreasing trend, further substantiates these results. It suggests that management has been successful in reducing human-crocodile interactions or that interactions are sparse due to continually low crocodile abundance, or due to heavy anthropogenic alteration driving crocodiles away from urban centers. Although Port Douglas has consistently remained the city with the highest densities of normalized crocodile sightings, attacks have not occurred in Port Douglas since the pre-exploitation period, suggesting that crocodile attacks may not be primarily related to crocodile abundance. It suggests that local management, such as CrocWise programs, or relatively low human populations in Port Douglas may explain trends more than crocodile abundances.

Limitations of Study

This research involved the collection of data from historical newspaper articles from the online database, Trove. Data collected from historical sources can never be comprehensive (McClenachan et al. 2015), but in this case data collected represented approximately 25% percent of possible articles. While searching through historical newspapers in Trove, it was discovered that citizens of Queensland, commonly referred to saltwater crocodiles as "alligators." However, most of the historical searches conducted did not include the word "alligator," which means that more historical sightings of saltwater crocodiles likely exist. Thus, although over 10,000 articles were searched for this study, approximately 25,000 articles with mentions of alligators and 5,000 more articles with mentions of crocodiles in Queensland still need to be examined.

Second, temporal gaps exist in the available historical data, as the Trove database only includes newspaper articles until 1957. Therefore, a large data gap exists between 1957 and 2010 when CrocBITE represented the only crocodile information source. This is an important time period because the federal embargo on crocodile exports was enacted in 1972 and crocodiles were officially protected in Queensland in 1974. Thus, the effects of this protection on crocodile sightings throughout this data gap period remain unknown. Additionally, as mentioned above, standardizing information from disparate sources limited the ability for this study to compare pre- and post-exploitation abundance of crocodiles in Queensland.

Smaller limitations include uncertainty about the exact locations of sightings; low location certainty of some sightings led to their exclusion from this analysis. As well, additional data gaps in human population censuses may have limited the accuracy of data normalization. Finally, it is possible that a smaller number of sightings of saltwater crocodiles may have actually been something else. For example, they may have been a large monitor lizard, a freshwater crocodile or a log. Instances of these misguided sightings were found throughout data searches; all sightings of this nature that could be identified were excluded, but it is possible that more existed.

Future Study

Data still need to be collected and various analyses should be conducted to explore the full scope of this study. First, it is imperative that historical searches be repeated using the word "alligator" to assess if additional historical sightings of saltwater crocodiles exist and that the remaining articles with mentions of crocodiles are analyzed. Together, the remaining articles left to be examined amount to approximately 30,000 articles or 75 percent of the total potential number of relevant articles. Although quantifying abundance data will still be difficult despite these added sightings due to data gap between 1957 and 2010 that will continue to persist, it would still be beneficial to rerun this analysis to determine if current sightings are at even lower levels in relation to historical sightings. Furthermore, it is possible that more anecdotal evidence exists that could provide more insight into the nature of the decline of crocodiles in southern regions of Queensland. It is unlikely that there will be more mentions of historical crocodile attacks as most major newspapers, meeting the demand for the news, thoroughly report on attacks through time.

Second, expanding the use of historical anecdotal evidence as a baseline of crocodile abundance may serve as a useful tool for documenting changes in abundance and distribution. These data would be collected opportunistically from anecdotes from the historical newspaper articles in Trove, in combination with similar anecdotal evidence that is mentioned in other published works, such as the crocodile textbook published by Grigg and Kirshner (2015). These analyses may be limited by over-exaggerations by crocodile hunters, but still may be able to supplement sightings data to inform some baseline of the abundance of crocodiles in Queensland.

Finally, changes in land use in Queensland should be further studied and analyzed with respect to location of crocodile nests and sightings in order to better understand the effect of anthropogenically altered crocodile habitat on their distribution and interaction with humans. Foremost, it is important that remaining crocodile nesting habitat be identified to limit degradation of these areas. The number of hatchlings recorded in the 2009/2010 survey was significantly lower than recorded during the 2007 survey, although the survey claims that this could be due to high mortality rates of hatchlings or the timing of the surveys (Queensland Government 2011). As well, sugar cane (Canegrowers 2010) and beef cattle farming (Taplin 1987) heavily overlap with crocodile ranges, so closely studying the spatial extent of these two industries may be conducive to conserving the natural habitats of saltwater crocodiles in Queensland.

Management Implications

Crocodile attack rates have remained low since the heavy exploitation period, suggesting that current management has been effective at preventing attacks. Although public education involving crocodiles can be extremely difficult (Butler 1987), the Queensland government's 'CrocWise' program seems to be successful in informing public safety. For example, Port Douglas falls within a 'Zone Three' area (Table 4) in which problem crocodiles are removed, and signs are deployed in areas of potential crocodile presence (Douglas Shire Council 2014). Although Port Douglas had the highest normalized attack rates pre-exploitation and has the highest normalized sightings rates in the post-exploitation period, it has not had any attacks occur in the post-exploitation period, suggesting successful management. Therefore, as simply removing problem crocodiles has shown to be successful, systematically culling all crocodiles over two meters in length is unwarranted. Culling of large individuals may also be unsuccessful in reducing fatal attacks. Fukuda et al. (2015) found that although the main cause of death due to crocodile attacks is drowning, which is directly correlated with the size of the crocodile, 66.7 percent of all fatal crocodile attacks since 2006 involved children, which likely indicates that crocodiles under two meters would have been just as capable of killing these victims.

The historical range of crocodiles appears to extend into areas south of the Boyne River and the Fitzroy River. However, current CrocWise messages are limited to areas of central and northern Queensland. Due to recent sightings further south that may suggest that crocodiles are recolonizing their southern range, CrocWise safety messages should be increased in locations further south along Queensland's coastline and crocodiles should not be automatically removed from these areas, as the areas likely represent natural crocodile habitat.

In addition, reports of crocodile sightings from disparate sources do not prove to serve as effective proxies for crocodile abundance. Spotlight counts represent the best strategy for detecting changes in abundance of saltwater crocodiles (Stirrat et al. 2001), but the Queensland Government has not conducted surveys of this nature since 2009/2010 (Queensland Government 2011). Therefore, government spotlight surveys should be increased in frequency and should be standardized to allow for annual abundance comparisons.

Finally, urbanization and agricultural development are likely affecting crocodile nesting areas. As natural landscapes continue to be altered in Queensland, understanding the impacts of these alterations on crocodile recovery is necessary. By allowing crocodiles to recover and understanding their abundance across Queensland, it may be possible to introduce a sustainable market for them, as modeled in the Northern Territory. In the Northern Territory, sustainable exploitation has not only provided economic benefits to citizens, but it has also promoted higher tolerance and more positive opinions of crocodiles in comparison to Queensland (Grigg and Kirshner 2015). As the political, economic and, eventually, cultural roles of crocodiles in Queensland shift, conservation strategies within Queensland may become more widely accepted, allowing the species to finally recover (Woodroffe 2000).

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APPENDICES

Appendix I: Historical newspapers that were searched in Trove to extract anecdotes and sightings information

Newspaper Name	Location	Years	Number of Entries (Crocodile, not mine, article)	Search Specific Info
Cairns Morning Post	Cairns	1907-1909	12	Searched alligator as well
Cairns Post	Cairns	1884-1893	16	Searched all articles
Cairns Post	Cairns	1909-1954	2,336	Searched all articles
Daily Mercury	Mackay	1906-1954	1,266	-
Gympie Times and Mary River Mining Gazette	Gympie	1868-1919	130	Only recorded sightings south of Mackay
Mackay Mercury	Mackay	1887-1905	24	-
Mackay Mercury and South Kennedy Advertiser	Mackay	1867-1887	18	Not helpful
Maryborough Chronicle	Maryborough	1947-1954	194	Only recorded sightings south of Mackay
Maryborough Chronicle, Wide Bay and Burnett Advertiser	Maryborough	1860-1947	608	Only recorded sightings south of Mackay
Morning Bulletin	Rockhampton	1878-1954	1,496	Only recorded sightings south of Mackay; excluded articles including the word "gold."

Queensland Times	Ipswich	1909-1954	594	Only recorded sightings south of Mackay
Rockhampton Bulletin	Rockhampton	1871-1878	115	Not helpful
Rockhampton Bulletin and Central Queensland Advertiser	Rockhampton	1861-1871	161	-
The Central Queensland Herald	Rockhampton	1930-1956	426	Only recorded sightings south of Mackay
The North Queensland Register	Townsville	1892-1905	73	Not helpful
The Northern Herald	Cairns	1913-1939	327	Not helpful
The Queenslander	Brisbane	1866-1939	954	-
Townsville Daily Bulletin	Townsville	1907-1954	1,559	Searched all articles
Morning Post	Cairns	1897-1907	21	Not helpful

Appendix II: Reclassified land cover values (ESA 2006).

Reclassified Name	Global GlobCover Legend	Value
Cropland	Irrigated croplands	11
	Rainfed croplands	14
	Mosaic croplands/ vegetation	20
	Mosaic vegetation/ croplands	30
Other	Closed to open broadleaved Evergreen or semi-deciduous forest	40
	Closed broadleaved deciduous forest	50
	Open broadleaved deciduous forest	60
	Closed needleleaved evergreen forest	70
	Open needleleaved deciduous or evergreen forest	90
	Closed to open mixed broadleaved and needleleaved forest	100
	Mosaic forest-shrubland/ grassland	110
	Mosaic grassland/ forest-shrubland	120
	Closed to open shrubland	130
	Closed to open grassland	140
	Sparse vegetation	150
	Closed to open broadleaved forest Regularly flooded (fresh-brackish water)	160
	Closed to broadleaved forest Permanently flooded (saline-brackish water)	170
	Closed to open vegetation regularly flooded	180
	Bare areas	200
	Permanent snow and ice	220
	No data	230
Artificial	Artificial areas	190
Water Bodies	Water bodies	210

Appendix III: R script

```
# Load packages
library(rgdal)
library(sp)
library(rgeos)
library(raster)
library(maptools)
library(RColorBrewer)
library(dplyr)
library(tidyr)
library(ggplot2)
library(extrafont)
library(xlsx)
library(stringr)

###########
# CLEANING DATAFRAMES

# Load dataframes
SightingsData <- read.csv("Master Data Sheet_R.csv", stringsAsFactors=FALSE)
PopulationData <- read.csv("Population Data.csv")
LatLongCityData <- read.csv("CityLatLong.csv")

# Exclude unwanted sightings data
SightingsData1 <- SightingsData %>%
  filter(Certainty >= 2,
         Sighting >=1 | Nest. >= 1)

# Count how many sightings occur in each decade
SightingsByDecade <- SightingsData1 %>%
```

```
  mutate(Tool = str_sub(Year, start=1, end=3)) %>%
  mutate(Decade2 = str_pad(Tool, width=4, side="right", pad = "0" )) %>%
  group_by(Decade2) %>%
  summarise(SumCroc = sum(Sighting)) %>%
  ungroup() %>%
  mutate(Decade2 = as.numeric(Decade2))

# These data loaded into GIS --> buffered by 25km within city centers of "Population
Data" cities
# "Urban Sightings" created from this output

###########
# SPATIAL DATA

## Population Data
# Create a copy as a spatial file
LatLongCityData.sp <- LatLongCityData
# Convert to a spatial file
coordinates(LatLongCityData.sp) <- ~Long+Lat
# Save this as a GIS object
# Two dots mean go up a level from current directory
writeOGR(LatLongCityData.sp, dsn= "../GIS/SHP",
layer="PopCity_041116",driver="ESRI Shapefile")

###########
# HUMAN POP

UrbanSightings <- read.csv("UrbanSightings.csv")

# Make sure Long and Lat are numeric
UrbanSightings$Lat <- as.numeric(UrbanSightings$Lat)
```

```
UrbanSightings$Long <- as.numeric(UrbanSightings$Long)

# Exclude unwanted urbansightings data
UrbanSightings <- UrbanSightings %>%
  select(Year, River, Specific_L, Lat, Long, Certainty,
        Notes, Sighting, Source, City, Fatal_Atta, Non_Fatal) %>%
  rename(Fatal = Fatal_Atta) %>%
  filter (Year <= 2011)

# Exclude unwanted pop data
PopulationData <- PopulationData %>%
  select(Year, Population, City) %>%
  filter(City == "Brisbane" | City == "Bundaberg" | City == "Cairns"| City ==
"Gladstone"|
          City == "Ingham"| City == "Mackay" |  City == "Maryborough" | City == "Port
Douglas" |
          City ==  "Rockhampton" | City ==  "Townsville" | City ==  "Cooktown") %>%
  mutate(City = factor(City, levels = c("Cooktown", "Port Douglas", "Cairns", "Ingham",
"Townsville",
                              "Mackay", "Rockhampton", "Gladstone", "Bundaberg",
"Maryborough", "Brisbane")))

# Graph population by city
## INCLUDE
ggplot(PopulationData, aes(x=Year, y=Population)) + geom_point() +
  facet_grid(. ~ City) +
  scale_x_continuous(breaks= seq(1850, 2020, 100)) +
  ylab("Human Population")  +
  ylim(0, 2000000) +
  theme_bw() +
  theme(text=element_text(family="Times New Roman", size=16))
```

```
###########
# Interpolate Population from earliest date until 2011

# Brisbane

PopBris <- PopulationData %>%
  filter(City == "Brisbane") %>%
  select(Year, Population)

SightBris <- UrbanSightings %>%
  filter(City == "Brisbane")

YearBris <- SightBris$Year

InterBris <- data.frame(approx(PopBris$Year, PopBris$Population, YearBris))

Bris <- SightBris %>%
  mutate(Population = InterBris$y)

# Bundaberg

PopBund <- PopulationData %>%
  filter(City == "Bundaberg") %>%
  select(Year, Population)

SightBund <- UrbanSightings %>%
  filter(City == "Bundaberg")

YearBund <- SightBund$Year

InterBund <- data.frame(approx(PopBund$Year, PopBund$Population, YearBund))
```

```
Bund <- SightBund %>%
  mutate(Population = InterBund$y)

# Cairns

PopCairns <- PopulationData %>%
  filter(City == "Cairns") %>%
  select(Year, Population)

SightCairns <- UrbanSightings %>%
  filter(City == "Cairns")

YearCairns <- SightCairns$Year

InterCairns <- data.frame(approx(PopCairns$Year, PopCairns$Population, YearCairns))

Cairns <- SightCairns %>%
  mutate(Population = InterCairns$y)

# Gladstone

PopGlad <- PopulationData %>%
  filter(City == "Gladstone") %>%
  select(Year, Population)

SightGlad <- UrbanSightings %>%
  filter(City == "Gladstone")

YearGlad <- SightGlad$Year
```

```
InterGlad <- data.frame(approx(PopGlad$Year, PopGlad$Population, YearGlad))

Glad <- SightGlad %>%
  mutate(Population = InterGlad$y)

# Ingham

PopIng <- PopulationData %>%
  filter(City == "Ingham") %>%
  select(Year, Population)

SightIng <- UrbanSightings %>%
  filter(City == "Ingham")

YearIng <- SightIng$Year

InterIng <- data.frame(approx(PopIng$Year, PopIng$Population, YearIng))

Ing <- SightIng %>%
  mutate(Population = InterIng$y) %>%
  na.omit(Population)
# One value was too early for census data so use na.omit

# Mackay

PopMack <- PopulationData %>%
  filter(City == "Mackay") %>%
  select(Year, Population)

SightMack <- UrbanSightings %>%
  filter(City == "Mackay")
```

```
YearMack <- SightMack$Year

InterMack <- data.frame(approx(PopMack$Year, PopMack$Population, YearMack))

Mack <- SightMack %>%
  mutate(Population = InterMack$y)

# Maryborough

PopMary <- PopulationData %>%
  filter(City == "Maryborough") %>%
  select(Year, Population)

SightMary <- UrbanSightings %>%
  filter(City == "Maryborough")

YearMary <- SightMary$Year

InterMary <- data.frame(approx(PopMary$Year, PopMary$Population, YearMary))

Mary <- SightMary %>%
  mutate(Population = InterMary$y)

# Port Douglas

PopPort <- PopulationData %>%
  filter(City == "Port Douglas") %>%
  select(Year, Population)

SightPort <- UrbanSightings %>%
```

```
  filter(City == "Port Douglas")

YearPort <- SightPort$Year

InterPort <- data.frame(approx(PopPort$Year, PopPort$Population, YearPort))

Port <- SightPort %>%
  mutate(Population = InterPort$y)

# Rockhampton

PopRock <- PopulationData %>%
  filter(City == "Rockhampton") %>%
  select(Year, Population)

SightRock <- UrbanSightings %>%
  filter(City == "Rockhampton")

YearRock <- SightRock$Year

InterRock <- data.frame(approx(PopRock$Year, PopRock$Population, YearRock))

Rock <- SightRock %>%
  mutate(Population = InterRock$y)

# Townsville

PopTown <- PopulationData %>%
  filter(City == "Townsville") %>%
  select(Year, Population)
```

```
SightTown <- UrbanSightings %>%
  filter(City == "Townsville")

YearTown <- SightTown$Year

InterTown <- data.frame(approx(PopTown$Year, PopTown$Population, YearTown))

Town <- SightTown %>%
  mutate(Population = InterTown$y)

# Cooktown

PopCook <- PopulationData %>%
  filter(City == "Cooktown") %>%
  select(Year, Population)

SightCook <- UrbanSightings %>%
  filter(City == "Cooktown")

YearCook <- SightCook$Year

InterCook <- data.frame(approx(PopCook$Year, PopCook$Population, YearCook))

Cook <- SightCook %>%
  mutate(Population = InterCook$y)

# Join all Population Cities

SightPopJoin <- data.frame(rbind(Bris, Bund, Cairns, Cook, Glad, Ing, Mack, Mary, Port,
Rock, Town)) %>%
  na.omit(Population)
```

```
###########
# ABUNDANCE
# Normalize Sightings Data

# Mean human population by city and year (does not actually change value)
SightPopJoinNorm <- SightPopJoin %>%
  group_by(City, Year) %>%
  summarise( Population = mean(Population)) %>%
  ungroup()

# Sum of population by city and year
SightPopJoinNorm2 <- SightPopJoin %>%
  group_by(City, Year) %>%
  summarise( Sighting = sum(Sighting)) %>%
  ungroup()

########### ABUNDANCE GRAPHS
# For graphs - Need to normalize by pop, overall by year
SightPopJoinNorm.G <- full_join(SightPopJoinNorm, SightPopJoinNorm2, by= c("City",
"Year")) %>%
  group_by(Year) %>%
  summarise (NormalSight= (sum(Sighting) / sum(Population)) * 10000) %>%
  ungroup()

# By Year
ggplot(SightPopJoinNorm.G, aes(x=Year, y=NormalSight)) + geom_point() +
  scale_x_continuous(breaks= seq(1850, 2020, 20)) +
  stat_smooth(method="loess", se=FALSE, span=1,
              method.args=list(family="symmetric", degree=1)) +
  geom_vline(xintercept=c(1945, 1972), col="red") +
```

```
  ylab("Normalized Sightings")  +
  theme_bw() +
  theme(text=element_text(family="Times New Roman", size=12)) +
  annotate("text", x = c(1907.5, 1961, 1991), y = 60, label = c("Pre Ex", "During Ex",
"Post Ex"),
           family="Times New Roman", color= "red")

# Modern Sightings (2010-2015)
ModernSightings <- SightingsData %>%
  filter( Year >= 2010) %>%
  filter(Year <= 2015) %>%
  group_by(Year) %>%
  summarise(Sighting = sum(Sighting))

ggplot(ModernSightings, aes(x=Year, y=Sighting)) + geom_point() + ylim(0, 400) +
  ylab("Number of Confirmed and Unconfirmed Sightings" ) + theme_bw() +
  theme(text=element_text(family="Times New Roman", size=12)) +
  stat_smooth(method="loess", se=FALSE, span=1, method.args=
list(family="symmetric", degree=1))

########### ABUNDANCE MAPS
# For maps - Need to normalize by pop, # in which attacks occurred, overall by city ->
break down by time period
# Create excel files to load into ArcGIS
# Pre Exploitation
SightPopJoinNorm.pre <- full_join(SightPopJoinNorm, SightPopJoinNorm2, by=
c("City", "Year")) %>%
  filter(Year <= 1944) %>%
  group_by(City) %>%
  summarise (NormalSight= (sum(Sighting) / sum(Population)) * 10000) %>%
  ungroup() %>%
```

```
  mutate(SightTrans = NormalSight/ (40))

SightPopJoinNorm.pre <- inner_join(SightPopJoinNorm.pre, LatLongCityData, by =
"City")

write.xlsx(SightPopJoinNorm.pre, "SightPopJoinpre.xlsx")

# Heavy Exploitation
SightPopJoinNorm.dur <- full_join(SightPopJoinNorm, SightPopJoinNorm2, by=
c("City", "Year")) %>%
  filter(Year >= 1945 & Year <= 1971) %>%
  group_by(City) %>%
  summarise (NormalSight= (sum(Sighting) / sum(Population)) * 10000) %>%
  ungroup() %>%
  mutate( SightTrans = NormalSight/ (11))

SightPopJoinNorm.dur <- inner_join(SightPopJoinNorm.dur, LatLongCityData, by =
"City")

write.xlsx(SightPopJoinNorm.dur, "SightPopJoindur.xlsx")

# Post Exploitation
SightPopJoinNorm.post <- full_join(SightPopJoinNorm, SightPopJoinNorm2, by=
c("City", "Year")) %>%
  filter(Year >= 1972) %>%
  group_by(City) %>%
  summarise (NormalSight= (sum(Sighting) / sum(Population)) * 10000) %>%
  ungroup() %>%
  mutate( SightTrans = NormalSight/ (7))
```

```
SightPopJoinNorm.post <- inner_join(SightPopJoinNorm.post, LatLongCityData, by =
"City")

write.xlsx(SightPopJoinNorm.post, "SightPopJoinpost.xlsx")

###########
 ATTACKS
# Normalize Attack Data
# Mean human population by city and year (does not change the value)
SightPopJoinAttack <- SightPopJoin %>%
  mutate( Attack = Fatal + Non_Fatal) %>%
  filter(Attack >= 1) %>%
  group_by(City, Year) %>%
  summarise( Population = mean(Population)) %>%
  ungroup()

# Sum of attacks by city and year
SightPopJoinAttack2 <- SightPopJoin %>%
  mutate( Attack = Fatal + Non_Fatal) %>%
  filter(Attack >= 1) %>%
  group_by(City, Year) %>%
  summarise( Attack = sum(Attack)) %>%
  ungroup()

########### ATTACK GRAPHS
# For graphs - Need to normalize by pop, overall by year
# Group by decade b/c that is what I will show in graphs
SightPopJoinAttack.G <- full_join(SightPopJoinAttack, SightPopJoinAttack2, by=
c("City", "Year")) %>%
  mutate(Tool = str_sub(Year, start=1, end=3)) %>%
  mutate(Decade = str_pad(Tool, width=4, side="right", pad = "0" )) %>%
```

```
  group_by(Decade) %>%
  summarise (NormalAttack= (sum(Attack) / sum(Population)) * 10000) %>%
  ungroup() %>%
  mutate( Decade = as.numeric(Decade))

# Add zeros for years in which no attacks occurred
SightPopJoinAttack.G <- complete(SightPopJoinAttack.G,
nesting( Decade=seq(1870,2000,by=10)), fill= list(NormalAttack =0))

# Normalized Attacks
# Plot
ggplot(SightPopJoinAttack.G, aes(x=Decade, y=NormalAttack)) + geom_point() +
  scale_x_continuous(breaks= seq(1850, 2020, 20)) +
  stat_smooth(method="loess", se=FALSE, span=1,
              method.args=list(family="symmetric", degree=1)) +
  geom_vline(xintercept=c(1945, 1972), col="red") +
  ylab("Normalized Attacks")  +
  theme_bw() +
  theme(text=element_text(family="Times New Roman", size=12)) +
  annotate("text", x = c(1907.5, 1958, 1991), y = 40, label = c("Pre Ex", "During Ex",
"Post Ex"),
           family="Times New Roman", color= "red")



# All attacks by decade (not normalized)
# Plot
Attacks <- SightingsData1 %>%
  mutate( Attack = Fatal.Attack + Non.Fatal.Attack) %>%
  filter(Attack >= 1) %>%
  mutate(Tool = str_sub(Year, start=1, end=3)) %>%
  mutate(Decade = str_pad(Tool, width=4, side="right", pad = "0" )) %>%
```

```
  group_by(Decade) %>%
  summarise(sumattacks = sum(Attack)) %>%
  ungroup() %>%
  mutate(Decade = as.numeric(Decade))

Attacks <- data.frame(Attacks)

# Add zeros for years in which no attacks occurred
Attacks <- complete(Attacks, nesting( Decade=seq(1870,2010,by=10)), fill=
list(sumattacks =0))

# Plot
ggplot(Attacks, aes(x=Decade, y=sumattacks)) + geom_point() +
  ylab("Attacks")  +
  xlab("Deacde") +
  scale_x_continuous(breaks= seq(1850, 2020, 10)) +
  theme_bw() +
  theme(text=element_text(family="Times New Roman", size=12)) +
  geom_vline(xintercept=c(1945, 1972), col="red") +
  annotate("text", y = 15, x = c(1907.5, 1958, 1991), label = c("Pre Ex", "During Ex",
"Post Ex"),
           family="Times New Roman", color= "red") +
  stat_smooth(method= "loess", se=FALSE, span=1,
method.args=list(family="symmetric", degree=1))

########### ATTACK MAPS
# For maps - Need to normalize by pop, # range of years overall by city -> break down by
time period
# Create excel files to load into ArcGIS
# Pre Exploitation
```

```
SightPopJoinAttack.pre <- full_join(SightPopJoinAttack, SightPopJoinAttack2, by=
c("City", "Year")) %>%
  filter(Year <= 1944) %>%
  group_by(City) %>%
  summarise (NormalAttack= (sum(Attack) / sum(Population)) * 10000) %>%
  ungroup() %>%
  mutate(AttackTrans= NormalAttack /(1944-1871) )

SightPopJoinAttack.pre <- inner_join(SightPopJoinAttack.pre, LatLongCityData, by =
"City")

write.xlsx(SightPopJoinAttack.pre, "Attackpre.xlsx")

# Heavy Exploitation
SightPopJoinAttack.dur <- full_join(SightPopJoinAttack, SightPopJoinAttack2, by=
c("City", "Year")) %>%
  filter(Year >= 1945 & Year <= 1971) %>%
  group_by(City) %>%
  summarise (NormalAttack= (sum(Attack) / sum(Population)) * 10000) %>%
  ungroup() %>%
  mutate(AttackTrans= NormalAttack /(1971-1945))

SightPopJoinAttack.dur <- inner_join(SightPopJoinAttack.dur, LatLongCityData, by =
"City")

write.xlsx(SightPopJoinAttack.dur, "Attackdur.xlsx")

# Post Exploitation
SightPopJoinAttack.post <- full_join(SightPopJoinAttack, SightPopJoinAttack2, by=
c("City", "Year")) %>%
  filter(Year >= 1972) %>%
```

```
  group_by(City) %>%
  summarise (NormalAttack= (sum(Attack) / sum(Population)) * 10000) %>%
  ungroup() %>%
  mutate(AttackTrans= NormalAttack /(2011-1972))

SightPopJoinAttack.post <- inner_join(SightPopJoinAttack.post, LatLongCityData, by =
"City")

write.xlsx(SightPopJoinAttack.post, "Attackpost.xlsx")

###########
# LOCATION

LandValue <- read.csv("LandValue.csv")

summary(Location)

Location <- LandValue %>%
  rename(LandType = RASTERVALU) %>%
  filter(LandType == 11 | LandType == 14 | LandType == 20 | LandType == 30 |
LandType == 190)

summary(Location)

# Post= 280 and Pre= 90

# Post Land Degradation
280/1655
# 16.9 % of sightings occurred on agricultural land or artificial areas now

# Pre Land Degradation
```

```
90/463
# 19.4 % of sightings occurred on agricultural land or arificial areas now

## Program to run Chi-square test of independence
## 2x2 matrix of data
## Crocodile attacks pre- and post-1969 heavy deforestation

# Have to load this package later because it masks the "select" function in dplyr
library("MASS")

## Substitute your total number of sightings for each category below
pre.modified<-90  #number sightings urban+cropland, pre-1969
pre.other<-373     #number sightings other habitats, pre-1969
post.modified<-280 #number sightings urban +cropland, post-1969
post.other<-1375   #number sightings other habitats, post-1969
pre1969<-c(pre.modified,pre.other) #urban+cropland, other pre-1969
post1969<-c(post.modified,post.other) #urban+cropland, other post-1969
tbl<-cbind(pre1969,post1969) #combines two variables into a table
tbl #list values in table
chisq.test(tbl) #run the Chi-square test
```

Appendix IV: Versions of R packages

Package	Version
rgdal	1.0-4
sp	1.2-1
rgeos	0.3-11
raster	2.5-2
maptools	0.8-37
RColorBrewer	1.1-2
dplyr	0.4.3
tidyr	0.4.1
ggplot2	2.0.0
extrafont	0.1.7
xlsx	0.5.7
stringr	1.0.0
MASS	7.3-45
stats	3.2.3