ARE BARN OWLS (*Tyto alba*) BIOLOGICAL CONTROLLERS OF RODENTS IN THE
EVERGLADES AGRICULTURAL AREA?

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
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To Suzanne – I wouldn't be the person that I am today without you. Thank you!

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Biological control is defined as the use of living organisms to reduce abundance of pest

species. The ability of vertebrate predators to control vertebrate pests is limited, however the

potential of vertebrates to reduce prey abundance is maximized when predators are capable of

reproducing rapidly as prey abundance increases, when their movement is not restricted by

territoriality, and if they have high foraging efficiency. Barn Owls may be effective biological

controllers of rodents because they exhibit these traits. Nest boxes have been installed

throughout the Everglades Agricultural Area (EAA) in south Florida to increase Barn Owl

abundance with the intent of reducing pest rodents in sugarcane fields. This program has

successful increased the regional abundance of owls, but it is unknown if areas with more owls

have lower rodent abundances than areas without owls.

Nest boxes are useful tools for expanding nest site availability for many species of birds.

However, birds may be drawn to low quality sites by poorly placed boxes. Both immediate

quality and long-term stability of habitat must be considered when locating nest boxes or they

may act as ecological traps, resulting in low reproductive fitness for the population. When most

Barn Owls in the EAA select nesting locations, harvesting activities have not begun and rodents,

the primary prey of the owls, are abundant in crop fields. However, harvest occurs adjacent to

most active nest boxes before nesting is completed and therefore most nests are exposed to a rapid decline in food availability. This may have negative consequences to Barn Owls in the form of lowered nest success.

This study indicates that Barn Owls are not capable of reducing rodent abundance. Reproductive capacity of rodents far outpaces removal of rodents via predation. Furthermore, nest survivorship for Barn Owls was lower following sugarcane harvest when compared pre-harvest conditions. Long-term data is needed to test for the actual occurrence of an ecological trap, however this study demonstrates that a mechanism for a trap exists. If crop harvest does not result in lowered fitness of Barn Owl populations, then nest boxes may be beneficial conservation tools for Barn Owls.

CHAPTER 1
INTRODUCTION

Biological control is defined as the use of living organisms to control pest populations (Sweetman 1958; Caltagirone 1981). In predator-prey systems, control occurs when prey density is reduced to a level below which it would occur in the absence of predation, and fluctuations in prey abundance are regulated around this suppressed density over time (Potts 1980; Dempster 1983; Hassel 1985). Control of agricultural pests, defined as organisms that inflict unacceptable economic damage (Horn 1988), is achieved when crop loss is mitigated to a tolerable level (Mumford and Norton 1984). However, before socioeconomic management goals can be set, the overall ability of a predator to reduce abundance of the targeted species must be demonstrated. Therefore, in this study I define control as any measurable predator-induced reduction in abundance of prey.

The potential of predators to reduce abundance of crop-destroying pests has been recognized for decades (e.g., Shelford 1942; Howard 1967; Rice and Wilde 1988; Borkhataria et al. 2006). A review of studies conducted from 1960-2001 concluded that inundative releases of generalist predators into crop plots resulted in significant pest reduction in most instances; however, in all of these cases, predators and prey were invertebrates (Symondson et al. 2002). Most information pertaining to the ability of vertebrate predators to decrease abundance of vertebrate pests supports the contention that the controlling ability of predators in these situations is limited, although evidence in this regard often lacks experimental rigor (Davis et al. 1976; Newsome 1990).

Barn Owls (*Tyto alba*), generalist predators that prey primarily on rodents (Marti 1992, Taylor 1994), may serve as biological controllers of pest rodents in agricultural landscapes. Although this species is declining in parts of North America and Europe because of habitat

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alteration and changes in agricultural practices, Barn Owls are common in other parts of their near global distribution (Taylor 1994). Barn Owls are potential biological controllers of rodents because they have a combination of behavioral characteristics and life history traits that many other vertebrate predators lack. Whereas density of carnivorous species often is limited because individuals actively maintain and defend territories (Errington 1946, Newton and Marquiss 1991, Lindzey et al. 1994, de Azevedo and Murray 2007), foraging ranges of individual Barn Owls can overlap to a high degree when food and nesting locations are readily available (Ziesemer 1980, Taylor et al. 1988, Taylor 1994). Barn Owls are relatively fecund compared to other vertebrate predators. In portions of the species' distribution where climate does not impede reproduction, such as south Florida, Barn Owls are capable of producing two broods each year and fledge 2-6 young per brood (Taylor 1994). Density and location of Barn Owl populations can be manipulated using nest boxes (Duckett 1991, Regisser 1991, Lee 1997); therefore, the collective predation pressure of a population can be managed. Adult Barn Owls consume 1-2 rodents per night, and a single pair may eliminate more than 1000 rodents each year (Lenton 1980). When the additional consumption of rodents by nestlings is considered along with the potential to concentrate the collective foraging pressure of a population on an area of interest, the potential of the species to reduce abundance of rodent populations is apparent.

Avian species select habitat and nesting locations based on an assessment of habitat quality (Petit and Petit 1996, Muller et al. 1997, Martin 1998, Kolbe and Janzen 2002). Ecological traps occur when environmental cues used to assess quality do not provide an accurate gauge of habitat suitability, primarily due to anthropogenic influences (Misenhelter and Rotenberry 2000, Schlaepfer et al. 2002, Battin 2004, Weldon and Haddad 2005). An integral component of habitat suitability is temporal stability. Organisms must predict long-term

suitability of habitat based on an immediate assessment of quality and do not have the ability to reject good habitat that will be altered in the future. Temporal instability in habitat quality may be especially consequential when selecting breeding sites (Orians and Wittenberger 1991). For example, grassland birds often establish nests in croplands because the structure of these systems mimics that of natural grassland habitat and because of the ample food supplies available in these areas. However, nests in croplands often are destroyed by harvesting activities (Best 1986, Bollinger et al. 1990). The decoupling of cue, quality, and temporal stability of habitat can lead to lowered reproductive success of individuals, failure of nests, and extirpation of populations (Kokko and Sutherland 2001, Shochat et al. 2005).

Nest boxes are useful tools for expanding nest site availability for many cavity nesting bird species (e.g., Willner et al. 1983, Barry 1992). However, birds may be drawn to low quality sites by poorly placed boxes (e.g., Semel and Sherman 2001). Nest boxes may increase the perceived attractiveness of a site to a species while the actual quality of the site remains unchanged, thus resulting in the nest boxes potentially acting as ecological traps. Furthermore, boxes may be placed in areas that are considered by humans to be high quality based on an immediate assessment of surrounding habitat, but these sites may lack the temporal stability of resources required by the targeted species. Provision of artificial nesting structures may have negative consequences if the wider ecological context of this management action is not fully considered.

In the Everglades Agricultural Area (EAA) of south Florida, abundance of Barn Owls historically has been limited because trees large enough to contain hollow spaces suitable for nesting are not common and buildings used by owls for nesting and roosting are disappearing rapidly because of hurricanes and general disuse. Cotton rats (*Sigmodon hispidus*), roof rats

(*Rattus rattus*), and rice rats (*Oryzomys palustris*) are common in the EAA and all are capable of inflicting considerable damage to sugarcane crops (Walsh et al. 1976, Holler et al. 1981, Lefebvre et al. 1989, Martin et al. 2007). Over the past 20 years, approximately 200 Barn Owl nest boxes have been installed throughout the EAA to enhance the regional owl population with the intent of these raptors serving as biological controllers of pest rodents. At least two-thirds of the boxes are used by owls during the nesting season (late Aug – June), and all appear to have been used for nesting at least once (Martin, pers. obs.). Localized densities in the EAA can reach 18 pairs/5 km^2 (Martin, pers. obs.), whereas densities in other parts of this species' distribution range from 0.7 pairs/5 km^2 to 2.6 pairs/5 km^2 (Taylor et al. 1988, Altwegg et al. 2003).

I hypothesized that increased density of Barn Owls in the Everglades Agricultural Area (EAA) would result in lowered abundances of cotton rats, roof rats, and rice rats. To test this hypothesis, I first estimated abundance of each species over one year in six locations in the EAA that had very low densities of owls. I then randomly selected three of these areas and inflated owl densities in them by installing nest boxes. Following this, I re-assessed rodent abundance over one year and compared pre- and post-treatment abundances for each species. I also performed a population viability analysis to model the density of barn owls required to produce a measurable decline in abundance of cotton rats.

I also hypothesized that survivorship of both Barn Owl nests and individual chicks would be lower following sugarcane harvest compared to when standing sugarcane was present adjacent to nests, primarily because of the extreme crash in rodent abundance that follows harvest. To test this hypothesis, I monitored the fate of nests and individual chicks within a subset of nests, and calculated daily survival rates for pre- and post-harvest conditions. I also measured and compared the growth rate of the individual chicks over time.

CHAPTER 2
QUANTIFYING DAMAGE POTENTIAL OF THREE RODENT SPECIES ON SUGARCANE

Introduction

The Everglades Agricultural Area (EAA), located primarily in western Palm Beach

County, FL, consists of approximately 160,000 ha (400,000 acres) of sugarcane cropland.

Roughly half of the nation's cane sugar originates in the EAA (Baucum et al. 2006). Three

species of rodent, cotton rat (*Sigmodon hispidus*), roof rat (*Rattus rattus*), and rice rate

(*Oryzomys palustris*), thrive in this agricultural landscape. Cotton rats are the most abundant of

the three species (Doty 1960, Samol 1972b, Holler et al. 1982). Although density of cotton rats

may vary among fields because of presence of predators and rodent control programs, this

species is a habitat generalist (Whitaker and Hamilton 1998) that occurs throughout the entire

region. Roof rats typically reside in fields, as well as near human structures (Whitaker and

Hamilton 1998). They are likely to have a distribution as wide as that of cotton rats in the EAA;

however, roof rats are less fecund so their populations recover more slowly following

perturbations and their peak densities are likely to be lower. Rice rats primarily are limited to

wet, marshy areas (Whitaker and Hamilton 1998), so their distribution in the EAA is restricted.

All of these species have been implicated in the destruction of sugarcane crops (Garlough

1938, Doty 1960, Samol 1972a, Samol 1972b, Walsh et al. 1976, Lefebvre et al. 1978, Holler et

al. 1982), but an empirical investigation of the relative amount of damage caused by each is

lacking (Samol 1972b). Current pest control efforts focus on reducing the number of rodents in

general across the entirety of the region by applying rodenticides broadly (Abarca 1981,

Lefebvre et al. 1985, Montague et al. 1990). However, due to variation in habitat specificity and

reproductive capacity described above, both density of individual species and overall species

composition of rodents varies among fields (Doty 1960, Holler et al. 1982, Lefebvre et al. 1982,

Lefebvre et al. 1989). If certain species are responsible for a disproportionately large amount of damage to sugarcane crops, the efficiency of management efforts may be improved by focusing pest control efforts on areas where the most problematic species are most abundant. This study investigates and compares the amount of sugarcane that cotton rats, roof rats, and rice rats are capable of consuming in 24 hrs using a feeding trial experiment.

Methods

Feeding trials were conducted from 12 Mar - 4 May 2005, 12 Oct 2005 - 4 Jan 2006, and 15 Dec 2006 - 9 Feb 2007. Individuals of each species were opportunistically captured using single-door, collapsible Tomahawk live traps (40.5 x 12.5 x 12.5 cm, Tomahawk Live Trap Co., Tomahawk, WI) in a single sugarcane field of cultivar 'CP 80-1743' (Deren et al., 1991) at the Everglades Research and Education Center (EREC), Belle Glade, FL. Traps were opened and baited with rolled oats between 1700-1800 hrs, and then checked the following morning between 0700-0800 hrs. Rats were removed from occupied traps using a cloth bag, and species, sex, and mass were recorded. Individuals then were placed in separate 46 x 46 x 46 cm wire mesh cages with a pre-weighed, two-internode long section (approximately 30 cm in length) of 'CP 80-1743' sugarcane stalk (mean mass = 160.8 g, range: 103.1 – 280.3, SE = 2.0). No more than 6 rats were captured and tested simultaneously due to limited cage availability. All individuals captured were used in the experiment; therefore, the sample population represented a cross section of the sex and age classes in the field. Approximately two heaping teaspoon of rolled oats were added to each cage to simulate naturally occurring alternative food sources. An additional pre-weighed stalk section was placed in an empty cage for each group of rats tested to serve as a control for mass lost from stalks due to desiccation. All stalk sections were cut from the bottom six internodes of mature stalks harvested from the same field where rats were captured. Cages were placed in the breezeway of a barn away from human activity and were

separated from each other with sheets of paper. After 24 hrs, rats were released and all stalks were weighed again. Mass lost from the control stalk was subtracted from mass lost from experimental stalks to determine total grams of sugarcane consumed by each rat (g sugarcane/g rat/24 hrs). Mean air temperature was obtained for each trial period from the Florida Automated Weather Station located at EREC.

Before data analyses were conducted, data were tested for normality, a square root transformation was applied when data violated the assumption of normal distribution, and outlying data points were removed (Proc Univariate, SAS Institute, 2003). A fixed effect ANCOVA was used to examine if species, sex, mass, mean air temperature, and interactions of these variables influence the rate of sugarcane consumption by rats (Proc GLM, SAS Institute, 2003). Mean grams of sugarcane consumed per gram of body mass were calculated for each sex of each species. Finally, linear regression analyses were used to explore the relationship between mean air temperature and grams of sugarcane consumed per gram of body mass for each species (Proc REG, SAS Institute, 2003). A significance level of $\alpha = 0.05$ was used for all statistical tests. Data are presented as means ± SE.

Results

During this study, 114 cotton rats, 60 roof rats, and 42 rice rats were captured and tested (Table 2-1). ANCOVA indicated that species, sex, and an interaction between species and mean air temperature influenced the amount of sugarcane consumed by rats during the trials. Sex and the species*mean air temperature interaction term fell just short of statistical significance, but I still considered them relevant factors (Table 2-2). Rate of sugarcane consumption (g sugarcane/g rat/24 hrs) was not related to body mass of individuals for all species, and not related to sex of cotton rats (males: 0.39 ± 0.03 g; females: 0.34 ± 0.03 g) or roof rats (males: 0.25 ± 0.04 g;

females: 0.26 ± 0.04 g). Male rice rats, however, consumed a significantly higher percentage of their body mass than female rice rats (males: 0.49 ± 0.08 g; females: 0.20 ± 0.06 g). Cotton rats consumed a higher percentage of their body mass than roof rats. Grams of sugarcane consumed per gram of body mass by female rice rats did not differ from roof rats, but male rice rats consumed a significantly higher percentage of their body mass than any other group (Fig. 2-1). Regression analysis showed a negative relationship between grams of sugarcane consumed per gram of body mass and mean air temperature for rice rats, but there was no relationship between these variables for cotton rats or roof rats (Fig. 2-2).

Discussion

Consumption rate of sugarcane was similar across all body sizes within each of the three species of rodents. Thus, amount of sugarcane consumed in an area can be estimated by multiplying the following three parameters: consumption per gram of body mass of the species, mean mass of individuals, and density. For example, based on the mean mass of cotton rats that were captured in 34 locations throughout the EAA in 17,000 trap nights in 2005-2006 (Martin, unpublished data) and population density estimates from a previous study in the EAA (Lefebvre et al., 1982), our experimental data predict that cotton rats may consume 41.1 – 198.6 kg of sugarcane stalk per ha, or 7,056 – 32,442 metric tons across the entire EAA, during the four months prior to harvest when the annual rodent density cycle is at its peak.

Individual cotton rats are capable of consuming at least as much sugarcane as roof rats and rice rats. Because it is the most common of the three rodent pest species, my experimental data suggest that cotton rats collectively are responsible for the greatest proportion of rodent damage to sugarcane crops in the EAA. Roof rats consume as much sugarcane as individual cotton rats; however, because they are less abundant, their collective contribution to sugarcane destruction in the EAA should be less. Rice rats probably consume less sugarcane across the

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EAA than cotton rats and roof rats because their distribution is restricted to fields with high soil moisture. However, rice rats may collectively cause more damage to sugarcane in wetter fields where they are more common.

The large surface to volume ratios of small animals often result in high metabolic rates and a need for greater amounts of food in colder temperatures in order to maintain body temperature (Geiser et al. 2006). Rice rats, the smallest of the three rodents, exhibited thermoregulatory feeding behavior during the feeding trials. Fields occupied by rice rats may experience spikes in damage during periods of colder temperatures.

Actual within-field patterns of rodent damage may vary from the results of this experiment because of conditions not measured in this study, such as predator density, moon phase, precipitation, or the availability of alternative food sources. Also, the damage that rodents inflict on sugarcane extends beyond the amount of cane consumed. Even small breaks in the rind of stalks resulting from the gnawing of rodents may result in reduced nutrient flow through the plant and secondary fungal infections which further reduce sucrose yield (Abarca 1981). The physical structure of sugarcane fields may influence occurrence of rodent damage. Sugarcane stalks sometimes bend or break when they are tall. This lodging results in stalks leaning against each other, growing at an angle instead of vertically, or lying flat on the ground. Rodents are excellent climbers and are not limited to damaging only the portions of vertical stalks that they can reach from the ground; however, lodged stalks provide easier access to the entire length of the plant. Fields with greater amounts of lodging may have greater amounts of rodent damage.

Practically speaking, the overall amount of sugarcane crop damage is unlikely to vary with composition rodent communities within fields. Cotton rats, roof rats, and rice rats all consume sugarcane, and the cumulative damage inflicted by rodents will be great when rodent

densities are high. The amount of damage to crops will increase as the density of rodents increases, regardless of which particular species are present. Density of rodents in sugarcane fields should be monitored periodically to identify areas where rodent control is most critical. Elimination of rodent refugia habitat, such as overgrown fallow fields and weedy drainage ditch banks, may help limit regional rodent abundance. These areas provide safe havens for rodents after agricultural fields have been harvested. Rodent abundance may be further reduced by making farms more attractive to predators. An integrated pest management approach, which incorporates ecologically friendly management techniques such as these, may lessen need for chemical rodenticides while maintaining or enhancing overall control of rodents.

Table 2-1. Mass of rodents tested in feeding trials.

Species	n	Mean mass ± SE (g)	Range
Cotton rat (male)	72	120.5 ± 4.5	36-208
Cotton rat (female)	42	111.4 ± 5.3	50-202
Roof rat (male)	36	182.3 ± 6.9	80-270
Roof rat (female)	24	157.1 ± 5.5	90-208
Rice rat (male)	33	81.8 ± 3.8	52-132
Rice rat (female)	9	58.1 ± 1.9	50-66

Table 2-2. ANCOVA examining the influence of species, sex, mass, and mean air temperature on grams of sugarcane consumed per gram of body mass by rats during feeding trials.

	Sugarcane consumed (g) / body mass (g)	
	F	p
species	3.25	0.04
sex	3.52	0.06
species*sex	0.85	0.43
mass	0.90	0.35
species*mass	1.82	0.17
mean temp	0.70	0.84
mean temp*species	2.60	0.08
mean temp*mass	0.33	0.57
mean temp*species*mass	1.15	0.32
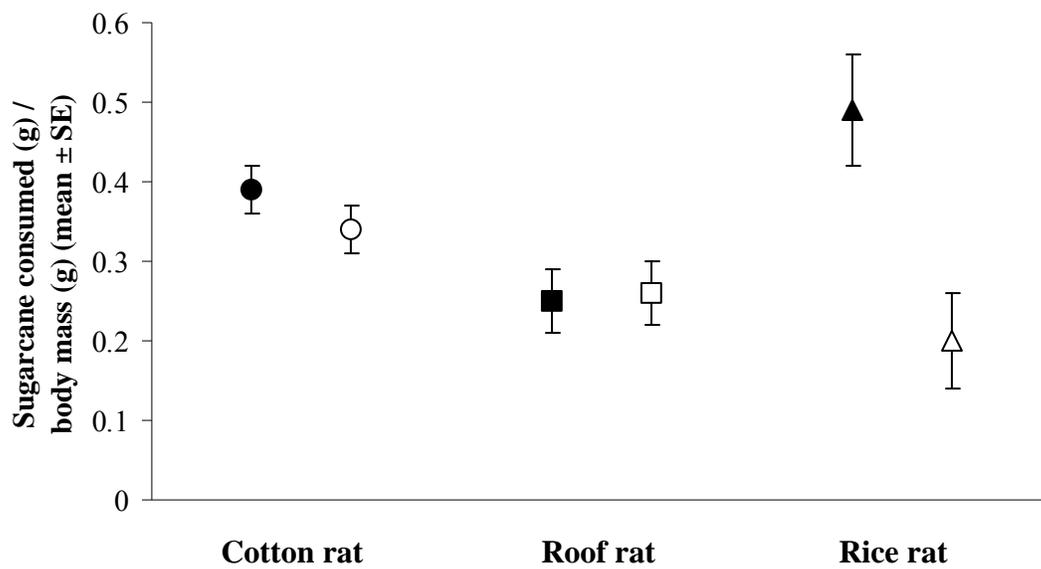
Figure 2-1. Mean grams of sugarcane consumed per gram of body mass in 24 hrs for cotton rats, roof rats, and rice rats. Solid symbols = males, hollow symbols = females.

Cotton rat

$R^2=0.02$
df=1, 113
P=0.13

Roof rat

$R^2=0.004$
df=1, 60
P=0.162

Rice rat

$R^2=0.20$
df=1, 41
P=0.003

Sugarcane consumed (g) / body mass (g)
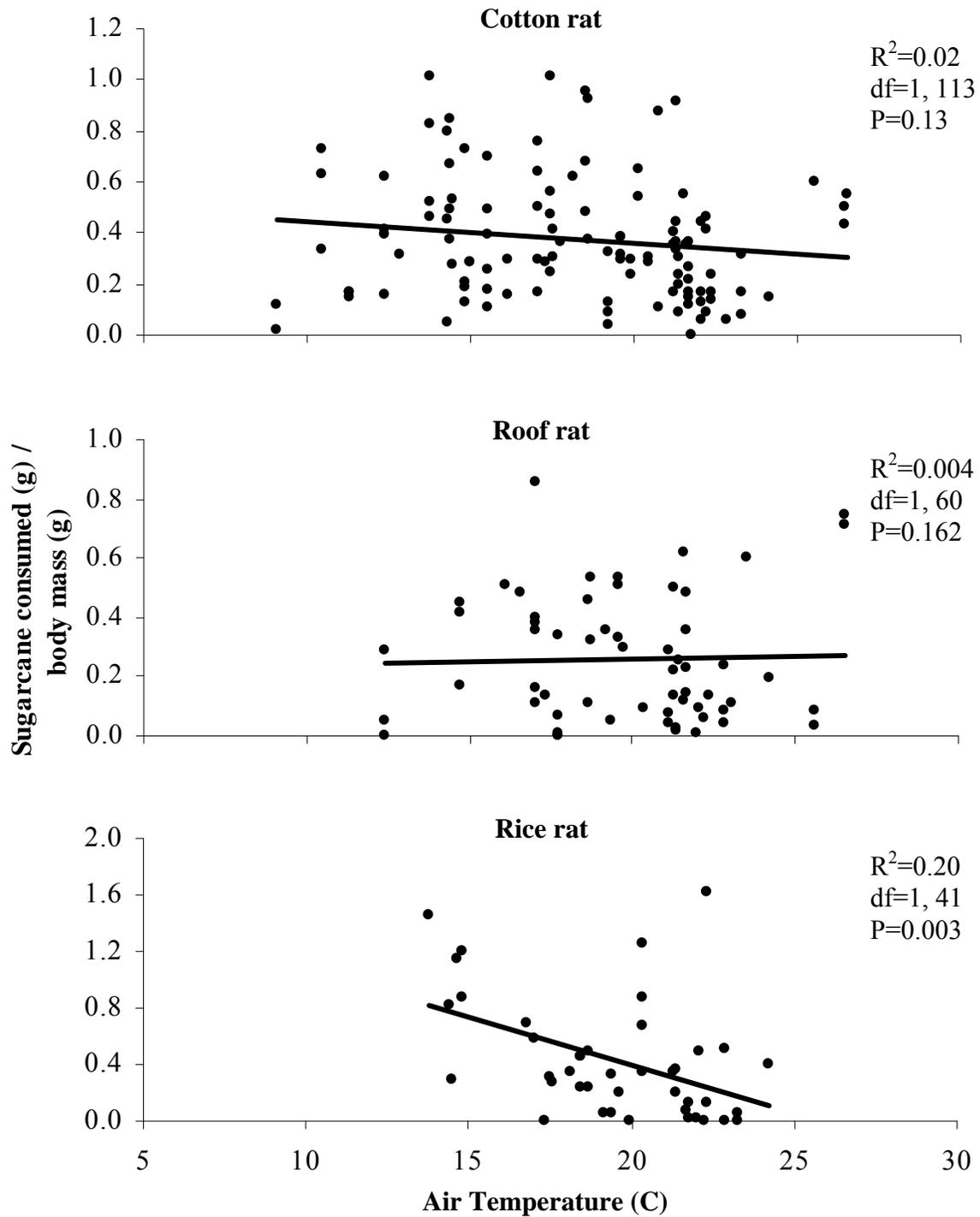
Air Temperature (C)

Figure 2-2. Linear regression analyses testing if grams of sugarcane consumed per gram of body mass is related to mean air temperature during feeding trials.

CHAPTER 3
AN ASSESSMENT OF BARN OWLS AS BIOLOGICAL CONTROLLERS OF PEST
RODENTS

Introduction

Biological control is defined as the use of living organisms to control pest populations

(Sweetman 1958; Caltagirone 1981). In predator-prey systems, control occurs when prey density

is reduced to a level below which it would occur in the absence of predation, and fluctuations in

prey abundance are regulated around this suppressed density over time (Potts 1980; Dempster

1983; Hassel 1985). Control of agricultural pests, defined as organisms that inflict unacceptable

economic damage (Horn 1988), is achieved when crop loss is mitigated to a tolerable level

(Mumford and Norton 1984). However, before socioeconomic management goals can be set, the

overall ability of a predator to reduce abundance of the targeted species must be demonstrated.

Therefore, in this study I define control as any measurable predator-induced reduction in

abundance of prey.

The potential of predators to reduce abundance of crop-destroying pests has been

recognized for decades (e.g., Shelford 1942; Howard 1967; Rice and Wilde 1988; Borkhataria et

al. 2006). A review of studies conducted from 1960-2001 concluded that inundative releases of

generalist predators into crop plots resulted in significant pest reduction in most instances;

however, in all of these cases, predators and prey were invertebrates (Symondson et al. 2002).

Most information pertaining to the ability of vertebrate predators to decrease abundance of

vertebrate pests supports the contention that the controlling ability of predators in these situations

is limited, although evidence in this regard often lacks experimental rigor (Davis et al. 1976;

Newsome 1990).

The ability of vertebrate predators to decrease abundance of vertebrate pests may be

limited for several reasons: 1) removal rate of prey by predators usually is far outpaced by

reproductive capacity of prey species (Pearson 1966), 2) predation often is compensatory rather than additive (Errington 1967; Bailey 1984), 3) predators may respond numerically to increases in intraspecific competition or declines in prey abundance by reducing reproductive output (Solomon 1949; Bayliss and Choquenot 2002), and 4) predators may respond functionally to changes in prey abundance by lowering per capita rate of food consumption or by shifting to alternative prey (Solomon 1949; Quinn and Cresswell 2004). The potential of vertebrate predators to reduce and regulate prey abundance is maximized when predators are capable of reproducing rapidly as prey abundance increases, when their movement is not restricted by territoriality, if they have high foraging efficiency, and if there is an alternative food source available to sustain their population when primary prey become scarce (MacArthur 1955; Davis et al. 1976; Hagen et al. 1976; Korpimaki and Norrdahl 1989; Symondson et al. 2002). If these conditions are met, prey may be driven to near extirpation (Sinclair et al. 1990).

Intraspecific competition for limited food resources often restricts predator density (Errington 1946; Votier et al. 2007; Bonal and Aparicio 2008); however, if predator density can be increased by altering a limiting resource not related to food (e.g., potential nesting sites), the collective rate of prey removal within a given area may increase. This management strategy has produced mixed results (e.g., Kale 1968; Meserve et al. 1993; Kay et al. 1994; Norrdahl and Korpimaki 1995). The success of habitat manipulation programs in enhancing predation is dependent on the ecology of both the predator and the targeted prey species, as well as the complexity of the surrounding ecosystem.

Barn Owls (*Tyto alba*), generalist predators that prey primarily on rodents (Marti 1992; Taylor 1994), may serve as biological controllers of pest rodents in agricultural landscapes. Although this species is declining in parts of North America and Europe because of habitat

alteration and changes in agricultural practices, Barn Owls are common in other parts of their

near global distribution (Taylor 1994). Barn Owls are potential biological control agents because

they have a combination of behavioral characteristics and life history traits that many other

vertebrate predators lack. Whereas density of carnivorous species often is limited because

individuals actively maintain and defend territories (Errington 1946; Newton and Marquiss 1991;

Lindzey et al. 1994; de Azevedo and Murray 2007), foraging ranges of individual Barn Owls can

overlap to a high degree when food and nesting locations are readily available (Ziesemer 1980;

Taylor et al. 1988; Taylor 1994). Barn Owls are relatively fecund compared to other vertebrate

predators. In portions of the species' distribution where climate does not impede reproduction,

such as south Florida, Barn Owls can produce two broods each year and fledge 2-6 young per

brood (Taylor 1994). Density and location of Barn Owl populations can be manipulated using

nest boxes (Duckett 1991; Regisser 1991; Lee 1997); therefore, the collective predation pressure

of a population can be managed. Adult Barn Owls consume 1-2 rodents per night, and a single

pair may eliminate more than 1000 rodents each year (Lenton 1980). When the additional

consumption of rodents by nestlings is considered along with the potential to concentrate the

collective foraging pressure of a population on an area of interest, the potential of the species to

reduce abundance of rodent populations is apparent.

Several previous studies have attempted to artificially increase Barn Owl density with the

intent of reducing abundance of pest rodents (e.g., Muñoz and Murúa 1990; Lee 1997; Moore et

al. 1998; Potter 2004). In these studies, nest boxes proved to be an effective means of

manipulating Barn Owl density and targeted pest species comprised a significant portion of the

diet of the owls. However, none of these studies quantified pest populations to determine if owl

predation resulted in reduced pest abundance and therefore provided no evidence regarding the use of Barn Owls as biological controllers (Marsh 1998).

Research Design

I hypothesized that increasing density of Barn Owls in the Everglades Agricultural Area (EAA) would result in lowered abundances of cotton rats, roof rats, and rice rats. To test this hypothesis, I used a completely randomized study design. Six areas in the EAA were selected that initially had very low densities of owls. Rodent abundances were estimated in each area over one year. I then randomly selected three of these areas and inflated owl densities in them by installing nest boxes. Following this, I re-assessed rodent abundance over one year and compared pre- and post-treatment abundances for each species. Finally, I performed a population viability analysis to model the density of barn owls required to produce a measurable decline in abundance of cotton rats in an individual sugarcane field and across the entire EAA.

I predicted that abundances of all species would be lower following inflation of owl density when compared to pre-manipulation abundances or abundance estimates from control areas that had no owls. I assumed that cotton rats, roof rats, and rice rats comprised a large proportion of the diet of Barn Owls in the EAA. To test this assumption, I quantified the regional owl diet by examining the content of owl pellets. I also assumed that density of other predators of rodents, such as diurnal raptors, were constant throughout all areas. Alternatively, rodent abundance may differ among sugarcane fields in the EAA because of variation in sugarcane variety (Barry Glaz, USDA Sugarcane Field Station, Canal Point, FL, pers. com.) or rotational age of fields (Samol 1972), however I controlled for both of these factors when selecting locations to sample rodents. I speculated that if rodent abundances were not significantly lower following inflation of owl density, this would be because reproductive capacity of all three species exceeded the rate of removal of individual rodents via predation.

Methods

Study Location and Species

I conducted this study in the Everglades Agricultural Area (EAA), a farming region in south Florida where sugarcane is the primary crop (Fig. 3-1). The EAA is divided by a network of drainage ditches into fields measuring approximately 200 x 800 m. These ditches may provide several critical resources for rodents, including refugia habitat following harvest of sugarcane and potential movement corridors (Robertson et al. 1995). Several cultivars of sugarcane are grown simultaneously across the EAA in 3-6 year rotational cycles resulting in a landscape mosaic of cultivars and rotational ages. Prior to the initial rotation year, referred to as "plant cane", soil is disked in December and January before sugarcane is planted. This process may destroy rodent burrow systems, thereby displacing localized populations. Fields are harvested following a 10-14 month growing season and remaining stalk stubble is left in the ground to re-sprout during subsequent rotational years, referred to as "ratoons". Soil disturbance during ratoon years is minimal. Cotton rats (*Sigmodon hispidus*), roof rats (*Rattus rattus*), and rice rats (*Oryzomys palustris*) are common in the EAA and all are capable of inflicting considerable damage to sugarcane crops (Walsh et al. 1976; Holler et al. 1981; Lefebvre et al. 1989; Martin et al. 2007). Damage to sugarcane plants may occur more frequently in older ratoon fields than in fields that are earlier in the rotation cycle (Samol 1972).

Barn Owls occur in grasslands, agricultural fields, and other open habitat throughout most of the world, and feed primarily on rodents (Marti 1992; Taylor 1994). The use of suitable foraging habitat by this species is limited by availability of nesting cavities (Marti 1992). Because rodent abundance in the EAA is high, the availability of potential nest sites likely is the primary limiting factor of Barn Owl density in the region. Trees large enough to contain hollow spaces suitable for nesting are not common. Furthermore, buildings used by owls for nesting and

roosting are disappearing rapidly throughout the region because of hurricanes and abandonment by farmers. Over the past 20 years, approximately 200 Barn Owl nest boxes have been installed in the EAA to enhance the regional owl population with the intent of reducing pest rodent abundance. Throughout this study, owls nested and roosted in at least two-thirds of these boxes (Martin, pers. obs.). Anecdotal reports describe rodent declines and less crop damage in areas of the EAA that are occupied by Barn Owls; however, prior to this study, quantitative data had not been collected to confirm these observations.

Study Design

      Study sites and experimental manipulation of owl density: I quantified abundance of cotton rats, roof rats, and rice rats in six areas in the EAA and subsequently manipulated Barn Owl density in three of these areas chosen at random. All areas had extremely low owl densities at the beginning of my study in 2005 because of a lack of potential nesting and roosting locations. In late autumn 2005, following one year of surveys of rodent abundance, I installed 25 nest boxes in each of the three experimental areas to inflate Barn Owl abundance for the following year (M1, M2, M3; Fig. 3-1). I observed 10-16 nests ($\bar{x} = 14.5$, SD = 2.3) in the boxes at each site during the 2006 nesting season. In 2006, I conducted a second round of rodent surveys in the experimental owl manipulation areas and in the three areas with no nest boxes that served as controls (C1, C2, C3; Fig. 3-1). All study areas were 10-km^2, representing a typical home range size of Barn Owls (Hegdal and Blaskiewicz 1984; Marti 1992; Taylor 1994), and were spaced at least 5 km from other study areas to ensure independence of predation pressure by owls on local rodent communities. Rodenticides were not applied to any areas involved in this study.

      Protocol for estimating rodent abundance: I used capture-mark-recapture techniques to estimate abundance of cotton rats, roof rats, and rice rats in all study areas during the 2005 and

2006 sugarcane growing seasons. Throughout the majority of the growing year, sugarcane stalks lodge together resulting in a thick mass of vegetation that likely restricts the majority of predatory interactions between Barn Owls and rodents to field edges and drainage ditch corridors that separate individual fields. Therefore, all rodent surveys were conducted along drainage ditches.

In January 2005, immediately following the 2004 sugarcane harvest, two ditches were selected in each study area. These ditches were located at least 800 m apart, which is more than two times previously described home range sizes and movement distances for cotton rats (Slade and Swihart 1983; Camerson and Spencer 1985; Difendorfer and Slade 2002; Sulok et al. 2004), roof rats (Whitaker and Hamilton 1988; Pryde et al. 2003), and rice rats (Whitaker and Hamilton 1988). One ditch was located between two plant cane fields and the other between older fields (at least second ratoon). To control for potential influence of sugarcane variety on rodent abundance, surveys were limited to ditches between fields containing commonly grown cultivars (CP80-1743 or CP89-2143).

Beginning at a randomly selected end of each ditch, I established two 250-m long transects, one on each side of the ditch, following the second plant row in from the edge of each field adjacent to the ditch. The two transects were separated by approximately 20 m. Two Tomahawk live-traps (40.5 x 12.5 x 12.5 cm, Tomahawk Live Trap Co., Tomahawk, WI) were placed every 10 m along each transect (100 traps per trapping array). For five consecutive days, I baited traps with rolled oats and opened them between 1600 and 1800 h. I checked and closed them the following morning between 0700 and 1000 h. I uniquely marked all cotton rats, roof rats, and rice rats captured by clipping fur, and recorded species, sex, and mass. Immediately

following processing, I released individuals at the capture location. Fur clips were not retained

beyond each 5-day trapping session.

I conducted three trapping sessions during each of two growing seasons (2005, 2006),

with the six study areas surveyed consecutively in a random order. During each trapping

session, I trapped the two ditches within each study area concurrently. The initial set of surveys

took place from 24 Jan – 26 Mar 2005 in recently harvested fields. Vegetative cover on ditch

banks was lacking during this early field growth phase due to mowing and/or herbicide

application. I then conducted a second series of mid-growth phase surveys (23 May – 23 July

2005) in the same order as the early growth phase surveys. At this time, fields contained 1 - 3 m

tall rows of cane, and grasses, forbs, and sedges had begun to grow along ditch banks. Finally, I

conducted a series of late growth phase surveys prior to harvest from 26 Sept – 10 Dec 2005

when sugarcane was 3.5 - 4.5 m tall and ditch banks were thickly vegetated. Trapping was not

conducted from 23 Oct – 22 Nov 2005 because of Hurricane Wilma. In 2006, I selected two new

field ditches in each study area and trapped them in a random order during the same three phases

of sugarcane growth (early: 6 Feb – 8 Apr, mid: 29 May – 29 July, late: 25 Sept – 25 Nov).

Barn Owl dietary analysis: Barn Owls typically swallow prey whole and later

regurgitate compacted pellets of indigestible bones and fur (Taylor 1994). Examination of prey

remains found in these pellets is a reliable indicator of diet (Errington 1932; Raczynski and

Ruprecht 1974; Dobson and Wexlar 1979). To determine if cotton rats, roof rats, and rice rats

comprised a significant portion of the Barn Owl diet in the EAA, I examined the contents of

1676 pellets collected between May 2004 and Feb 2007 from 15 buildings located throughout the

area known to be used by owls for nesting or roosting. Because remains of larger prey items

may be split among several pellets, only skulls were used to quantify prey base to avoid double

counting individuals. All small mammal skulls found were identified to species using reference specimens provided by the Florida Museum of Natural History. Rabbits were identified to genus (*Sylvilagus*), frogs and toads were identified to order (Anura), and birds were identified to class (Aves). The total number of skulls belonging to each species or taxonomic group was counted, and the relative percentage of each was calculated to determine the proportion of each in the diet of the EAA Barn Owl population.

Population viability analysis of cotton rats: I performed a population viability analysis (PVA) using Vortex 9.94 (Lacy et al. 2008) to model the density of Barn Owls required to produce a measurable reduction in abundance of cotton rats, the most abundant rodent in the EAA (Doty 1960, Samol 1972b, Holler et al. 1982), at the scale of a single sugarcane field. I also modeled the relative impact of two levels of predation intensity and two levels of cotton rat reproductive rates in this hypothetical system. I initially modeled a population of cotton rats over one year using minimum population size and carrying capacity estimates derived from data collected during this study from areas that did not have nest boxes, as well as life history parameters previously documented for the species (Montague et al. 1990; Whitaker and Hamilton 1998). I then adjusted these parameters so that the population growth curve predicted by the model matched data that I collected in areas without nest boxes (Table 3-1). I assumed that rates of dispersal into and out of the population were balanced.

I created scenarios simulating the cotton rat population within the foraging territories of owls surrounding various numbers of owl boxes: 1 box, 4 boxes, 6 boxes, 8 boxes, and 10 boxes. I assumed that all boxes in each scenario were occupied, and each had 2 adults and 4 chicks in them for 5 months (assuming double broods) and only 2 owls for the remainder of the year. Therefore, the mean number of owls per month represented in each scenario was 4, 16, 24,

32, and 40 respectively. In the EAA, there are approximately 45 fields within 1500 m (the size of an owl home range) of each nest box. Individual Barn Owls consume an average of 1.5 rodents each night (Taylor 1994). If predation pressure was distributed equally throughout home ranges, each owl would consume one rodent per field per month. Therefore, I first modeled the impact of predation on abundance of cotton rats for each owl density scenario by setting the harvest rate to one cotton rat per owl per month. The use of certain areas by raptors may be enhanced by providing artificial perches (Hall et al. 1981; Reinert 1984), therefore it may be possible to increase the removal rate of prey by individual owls in targeted areas. I simulated an increased concentration of predation on the cotton rat population by inflating the harvest rate to three rats per owl per month for each nest box density. In addition to increased adult mortality, abundance of wildlife populations may be impacted by changes in reproduction (Krebs and Meyers 1974). To examine how a reduced reproductive rate in cotton rats would influence the impact of Barn Owl predation on cotton rat abundance, I repeated the simulations described above using a reduced percentage of reproductive females (from 75% to 45%). A total of 100 simulations were completed for each scenario. Mean abundances ($\pm$SD) were estimated for each scenario at the end of one year.

Data analysis

I estimated abundance of cotton rats, roof rats, and rice rats for each field ditch using Huggins closed capture modeling in Program MARK (White and Burnham 1999). The conditions of population closure were assumed to be approximated during each 5-night trapping session. Abundance estimates were used as relative indices to compare rodent abundance among areas and over time.

To estimate abundance, I first modeled species-specific capture and recapture probabilities. Because habitat structure in sugarcane fields differed substantially during each of

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the three field growth phases in which I conducted surveys, I modeled detection probabilities for each rodent species within each field phase separately. Sample sizes often were too small to allow for adequate estimation of ditch-specific detection probabilities by species and phase, so capture-mark-recapture data for cotton rats and roof rats each were pooled across all trapping locations for each phase using ditch as a grouping term to estimate pooled detection probabilities. Because rice rats were less common than cotton rats and roof rats, data on rice rats were pooled further by combining early and mid-season field growth phase data.

I incorporated heterogeneity in detection probability of individual rodents using sex and age as covariates. Age classifications were determined for each species using mass categorizations from previous studies (cotton rat: <61 g = juvenile, 61-110 g = subadult, >110 = adult (Sauer and Slade 1985); roof rat: <71 g = juvenile, 71-120 g = subadult, >120 g = adult (Tamarin and Malecha 1972); rice rat: <30 g = juvenile, 30-50 g = subadult, > 50g = adult (Forys and Dueser 1993)). I constructed models for each species within each field phase that included no covariates, as well as age, sex, age and sex, and an interaction of age and sex on capture probability (p) and recapture probability (c) for scenarios where detection probability was constant (p = c) and where there was a behavioral response to trapping (p $\neq$ c). Behavioral response models were not estimable for cotton rat data from the early field growth phase, so in this instance I constructed only constant detection probability models.

I used an AICc approach in Program MARK to rank competing models. I then used pooled detection probabilities to derive abundance estimates for each species occupying each ditch for each model. Although using pooled detection probabilities derived from grouped data may bias abundance estimates for individual trapping arrays, this approach produces more accurate estimates than simply using number of individuals captured (Conn et al. 2006; Cooch

and White 2008). I calculated final abundance estimates ($\hat{N}$) for each species occupying each field ditch during each field growth phase by model averaging abundance estimates derived from all models of data collected from the respective ditches (Cooch & White, 2008).

The influence of covariates on $\hat{N}$ can not be modeled directly in Program MARK (White 2002). Therefore, to examine the influence of Barn Owl density on abundance of cotton rats, roof rats, and rice rats, I used a repeated measures ANOVA with field ditch as the subject variable and field phase as the repeated variable (Proc Mixed, SAS 2003). Appropriate covariance structures were selected using best fit statistics. To account for varying precision of $\hat{N}$ values, I weighted each estimate by the inverse of its variance using the 'weight' statement in SAS. To avoid excluding values of $\hat{N} = 0$ (i.e., ditches where no rodents were captured) from analyses, I set their weights to 0.0001. A significance level of p = 0.05 was used throughout.

I initially examined the influence of field age (plant cane vs. older ratoon) on abundance of each rodent species independently of other covariates in all study areas. Field age was not significant in any case and therefore was excluded in all further analyses. I then analyzed abundance of each species using the following covariates: field growth phase (early, mid, late), year (2005, 2006), treatment group (experimental, control), treatment*phase, year*phase, year*treatment, and year*treatment*phase. Least square mean estimates of rodent abundance were calculated for all factors. I then performed pair-wise least square mean comparisons using t tests between the following groups: Control '05 vs. Control '06, Experimental '05 vs. Experimental '06, Control '05 vs. Experimental '05, Control '06 vs. Experimental '06.

To analyze PVA results, I first used an analysis of variance (SAS 2003) to compare final abundance estimates derived from the low and high reproductive rate scenarios with no owl boxes. Using Dunnett's test, I then performed pairwise comparisons of abundances derived from

each nest box density scenario and the control estimate derived in the absence of nest boxes for each predation pressure/reproductive rate combination (1 rat/owl/month & 75% rat reproduction, 3 rats/owl/month & 75% rat reproduction, 1 rat/owl/month & 45% rat reproduction, 3 rats/owl/month & 45% rat reproduction). In this test, if the simultaneous 95% confidence interval of a comparison does not encompass zero, then the treatment value is significantly different than the reference value.

Results

Modeling rodent detection probabilities: All competing models of detection probabilities (i.e., those with $\Delta AICc < 2$) for all species contained age and/or sex covariates for capture and/or recapture likelihoods (Table 3-2). With the exception of early season data for cotton rats, where behavioral response models were omitted, models that incorporated behavioral response to trapping were ranked exclusively as competing models for all species in all seasons.

Rodent abundance: Field growth phase was highly significant in determining abundance of cotton rats and roof rats (Table 3-3). Abundance of both species increased as sugarcane in surrounding fields grew, with cotton rats ultimately becoming much more abundant by the late growth phase than roof rats (Fig. 3-2). The three-way interaction of year, field phase, and treatment was significant for cotton rats and roof rats indicating that patterns in abundance varied across years, field phases, and treatments (Table 3-3). However, none of the pair-wise comparisons of rodent abundance among study site groupings pertinent to this study were significant (Table 3-4).

Barn Owl dietary analysis: I found 2146 individual prey items in owl pellets. Sixty percent of these were rodents identified as sugarcane pests: cotton rats (42%), roof rats (10%), and rice rats (8%). House mice (*Mus musculus*) also comprised a relatively large portion of the Barn Owl diet (29%). The remainder consisted of rabbits (5%), birds (4%), round-tailed

muskrats (*Neofiber alleni*; 1%), southeastern shrews (*Sorex longirostris*; 0.7%), and toads/frogs (0.3%). Insect remains were found in many pellets, especially in those collected in June and July, but were not quantified.

Population viability analysis of cotton rats: The abundance estimate for cotton rats derived from the model with no owls and 45% of female cotton rats breeding was significantly lower than when owls were absent and 75% of female rats were breeding ($F = 154.6$, $df = 1, 198$, $p < 0.01$; Fig. 3-3). When 75% of female rats were breeding and individual owls harvested 1 rat per month, only scenarios with 8 and 10 boxes (32 and 40 owls respectively) resulted in cotton rat abundances that were significantly less than the control scenario with no owl predation (Table 3-5, Fig. 3-3). However, when the harvest rate was increased to 3 rats per owl per month with the same percentage of reproductive females, the number of boxes required to produce a measurable decline in cotton rat abundance dropped to 6 (24 owls). When only 45% of female rats were breeding, significant declines in cotton rat abundance were apparent with only 4 nest boxes (16 owls) at both predation intensities.

Discussion

Barn Owls in the EAA prey heavily on cotton rats, roof rats, and rice rats. However, the results of this study indicate that increasing Barn Owl density alone is unlikely to result in reductions of pest abundance in large agricultural landscapes. Reproductive capacity of rodents likely far exceeds rate of removal of individuals from the population via predation. Cotton rats are capable of producing litters of 10-15 young every month throughout the year, and roof rats and rice rats are only slightly less fecund (Whitaker and Hamilton 1998). Although late season abundance estimates for roof rats and rice rats appeared to decline slightly in the experimental sites following inflation of owl density, these differences were not significant. Even if a marginal reduction in rodent abundance actually occurred, this likely would not have resulted in

a measurable reduction in overall crop damage given the potential amount of sugarcane that individual rodents are capable of consuming (Martin et al. 2007).

Rodent populations occur at the scale of landscapes, but owl predation is a relatively localized phenomenon restricted primarily to areas near active nest boxes. Depredated rodents within foraging ranges of owls likely are replaced continually by dispersing individuals from the surrounding landscape. Increasing density of Barn Owls across the EAA at the scale required to reduce regional rodent abundance likely is not feasible, as indicated by the population viability analysis of cotton rats. When predation pressure of individual owls is spread equally throughout their foraging territories and the reproductive rate of cotton rats is high, each field in the EAA would need to be exposed to at least 8 occupied nest boxes. This translates to boxes spaced in a 950x950-m grid across the entire EAA (2113 boxes in total) with a 100% occupancy rate. This spacing is only slightly more dense than that of nest boxes in the experimental manipulation sites of this study, and in these sites maximum occupancy of nest boxes was only 64%, although this occupancy rate was based only on one year.

Field growth phase significantly influenced abundance of all three rodent species. Rodent populations increased in abundance throughout the sugarcane growing season as food and cover increased and then crashed following harvest. Because cotton rats, roof rats, and rice rats comprise such a large part of the Barn Owl diet in the EAA, declines in these species may result in declines in owl nesting success. Dietary diversity may buffer against declines of a portion of the prey base, however, house mice, the most common non-pest prey item, are much smaller than any of the pest species and do not provide comparable per capita nutritional intake. Additionally, all rabbit remains found in pellets belonged to juveniles that were no larger than

rats, and rabbits, along with the remaining prey items, comprised only a small fraction of the owls' total diet.

Further studies are needed to determine if Barn Owl predation can reduce rodent abundance if combined with other pest control techniques, such as strategically timed application of rodenticides and elimination of rodent refugia habitat following harvest, in an integrated pest management (IPM) approach. IPM seeks to implement a variety of compatible pest control tactics (chemical, biological, and cultural) to reduce abundance of crop-destroying pests (Hoskins et al. 1939, Smith 1978, Kogan 1998). PVA modeling indicated that increasing foraging intensity of individual owls and decreasing the reproductive capacity of rodent populations may be effective components of pest rodent management. The potential of owls to reduce abundance of rodents may increase if predation is concentrated on targeted areas, possibly by installing artificial perches in areas where pest control is desired (Hall et al. 1981; Reinert 1984). It is unlikely that this would result in reduced abundance of rodents in the EAA given the widespread nature of the rodent population. However, this approach may be more practical in small-scale agriculture. PVA modeling also indicated that lowering rodent reproductive rates may produce dramatic decreases in abundance, however the effectiveness and safety of wildlife contraception as a management tool is not certain (Guynn 1993, Warren 1995, Nettles 1997, Fagerstone et al. 2006).

Although inflation of owl density through installation of nest boxes does not appear to be an effective means of reducing abundance of pest rodents in large agricultural systems, this management tool may be important for conservation of owls as traditional nest sites of this species become scarce. As in previous studies (e.g., Muñoz and Murúa 1990; Lee 1997; Moore et al. 1998; Potter 2004), I found that Barn Owl density can easily be manipulated by installing

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nest boxes. However, the success of this management technique exhibited in this study may have been greater than that in other areas because of extremely high regional abundance of owls in the EAA that already existed prior to this study. Nevertheless, although Barn Owl management programs involving nest boxes should not expect colonization to the degree that I achieved, nest boxes are a proven management option where increasing abundance of the species is desirable.

This study demonstrates the inability of vertebrate predators to serve as biological controllers of vertebrate pests, even when individuals of the species have traits that maximize their ability to reduce abundance of these pests (i.e., relatively fecund, lack of territoriality, high foraging efficiency). Pests are abundant in anthropogenically altered landscapes or become concentrated in specific areas because typical bottom-up controlling mechanisms, such as limited availability of food, do not exist or exhibit only a weak influence on abundance. In agricultural areas, crops may provide a virtually unlimited food resource for pests thereby greatly increasing the threshold of density-dependent population regulatory factors. An unusually dense population of prey enables an equally unusually dense population of predators to exist and therefore bottom-up regulation across trophic levels, as opposed to top-down, is most likely to occur in vertebrate predator-prey systems in agricultural landscapes.

Table 3-1. Life history parameters for cotton rats derived from Montague et al. 1990 and Whitaker and Hamilton 1998, and modified to fit abundance data collected in areas of the EAA that did not have Barn Owls.

Parameter	Value
Inbreeding depression	Recessive lethals model
Breeding system	Polygynous
% males breeding	90%
Breeding age for males & females	1 month
Maximum age of reproduction	5 months
Maximum # of broods/month	1
Mean # offspring/brood	6
Maximum # offspring/brood	8
Sex ratio at birth (% males)	50%
Density dependent reproduction	Yes
% Females breeding at low density P(0)	75% or 45%
% Females breeding at carrying capacity P(K)	50% or 45%
Mortality from age 0 to 1 (SD)	45 (1)
Annual mortality after age 1 (SD)	45 (1)
Initial population size (with stable age distribution)	90
Carrying capacity (SD)	1750 (10)

Table 3-2. Competing Huggins closed-capture models (ΔAICc < 2) for cotton rats, roof rats, and rice rats during early, mid, and late sugarcane growth phases.

		COTTON RAT		
Phase	Model	AICc	ΔAICc	w_i
Early	p(age) = c(age)	711.64	0.00	0.662
	p(sex age) = c(sex age)	713.54	1.90	0.257
Mid	p(sex*age) c(sex*age)	3893.73	0.00	0.624
Late	p(sex*age) c(sex age)	11658.0	0.00	0.455
	p(sex age) c(sex age)	11658.4	0.49	0.357

		ROOF RAT		
Phase	Model	AICc	ΔAICc	w_i
Early	p(.) c(sex age)	818.55	0.00	0.188
	p(.) c(age)	819.47	0.92	0.118
	p(age) c(sex age)	819.66	1.11	0.107
	p(sex*age) c(sex age)	820.45	1.90	0.072
Mid	p(.) c(sex*age)	1164.90	0.00	0.293
	p(sex) c(sex*age)	1166.28	1.38	0.147
	p(age) c(sex*age)	1166.35	1.45	0.142
	p(sex*age) c(sex*age)	1166.74	1.84	0.117
Late	p(sex*age) c(sex)	2711.24	0.00	0.336
	p(sex*age) c(sex age)	2712.54	1.30	0.175

		RICE RAT		
Phase	Model	AICc	ΔAICc	w_i
Early/Mid	p(.) c(age)	1135.95	0.00	0.230
	p(.) c(sex age)	1136.68	0.73	0.159
	p(age) c(age)	1137.74	1.80	0.093
	p(sex*age) c(age)	1137.91	1.97	0.086
Late	p(.) c(age)	1318.92	0.00	0.279
	p(sex) c(age)	1320.50	1.58	0.126
	p(.) c(sex age)	1320.78	1.86	0.110
	p(age) c(age)	1320.80	1.88	0.109
	p(sex*age) c(age)	1320.87	1.95	0.105

Table 3-3. Proc Mixed repeated measures ANOVA examining the influence of Barn Owl density and sugarcane growth on abundance of three species of rodents.

Effect	df	COTTON RAT		ROOF RAT		RICE RAT	
		F-value	p-value	F-value	p-value	F-value	p-value
Phase	2	53.06	<0.01	29.92	<0.01	1.40	0.26
Year	1	0.05	0.83	0.74	0.40	0.26	0.62
Treatment	1	1.84	0.19	4.91	0.04	0.43	0.52
Treatment*Phase	2	1.27	0.30	4.16	0.03	0.96	0.39
Year*Phase	2	0.48	0.62	0.10	0.90	0.60	0.55
Year*Treatment	1	2.39	0.14	5.15	0.03	0.62	0.44
Year*Phase*Treatment	2	4.38	0.03	3.72	0.04	1.07	0.35

Table 3-4. Pair-wise least square mean comparisons among study site groupings for cotton rats and roof rats. Abundance of rodents in Experimental '06 sites should have been less than that in all other sites if owls were biological controllers of rodents.

COTTON RAT

Comparison	Expected	Actual
Control '05 vs. Control '06	=	= (t=0.17, p=0.88)
Experimental '05 vs. Experimental '06	>	= (t=2.37, p=0.10)
Control '05 vs. Experimental '05	=	= (t=0.69, p=0.54)
Control '06 vs. Experimental '06	>	= (t=1.50, p=0.23)

ROOF RAT

Comparison	Expected	Actual
Control '05 vs. Control '06	=	= (t=-2.18, p=0.12)
Experimental '05 vs. Experimental '06	>	= (t=1.62, p=0.20)
Control '05 vs. Experimental '05	=	= (t=-2.47, p=0.09)
Control '06 vs. Experimental '06	>	= (t=0.76, p=0.50)

Table 3-5. Results of Dunnett's tests comparing abundance estimates of cotton rats derived from PVA model scenarios involving various densities of Barn Owls, and incorporating two harvesting intensities and two levels of cotton rat reproduction (A, 75% breeding; B, 45% breeding), to abundances derived from models with no owl predation. Simultaneous 95% confidence intervals that do not encompass zero indicate significance.

A)

Nest boxes (Owls)	1 rat/owl/month		3 rats/owl/month	
	Difference between means	Simultaneous 95% confidence interval	Difference between means	Simultaneous 95% confidence interval
1 (4)	-6.7	-57.7, 44.2	-18.1	-156.9, 120.7
4 (16)	-33.0	-83.9, 17.9	-126.8	-265.6, 12.0
6 (24)	-48.9	-99.8, 2.1	-344.1	-482.9, -205.3
8 (32)	-59.6	-110.6, -8.6	-686.9	-825.7, -548.1
10 (40)	-79.7	-130.6, -28.7	-1001.4	-1140.1, -862.6

B)

Nest boxes (Owls)	1 rat/owl/month		3 rats/owl/month	
	Difference between means	Simultaneous 95% confidence interval	Difference between means	Simultaneous 95% confidence interval
1 (4)	-7.4	-142.6, 127.7	-41.6	-170.0, 86.8
4 (16)	-199.5	-334.6, -64.3	-524.1	-652.5, -395.7
6 (24)	-242.2	-377.4, -107.1	-736.3	-864.7, -607.9
8 (32)	-265.0	-400.2, -129.9	-1054.5	-1182.8, -926.1
10 (40)	-462.5	-597.7, -327.4	-1206.4	-1334.7, -1078.0
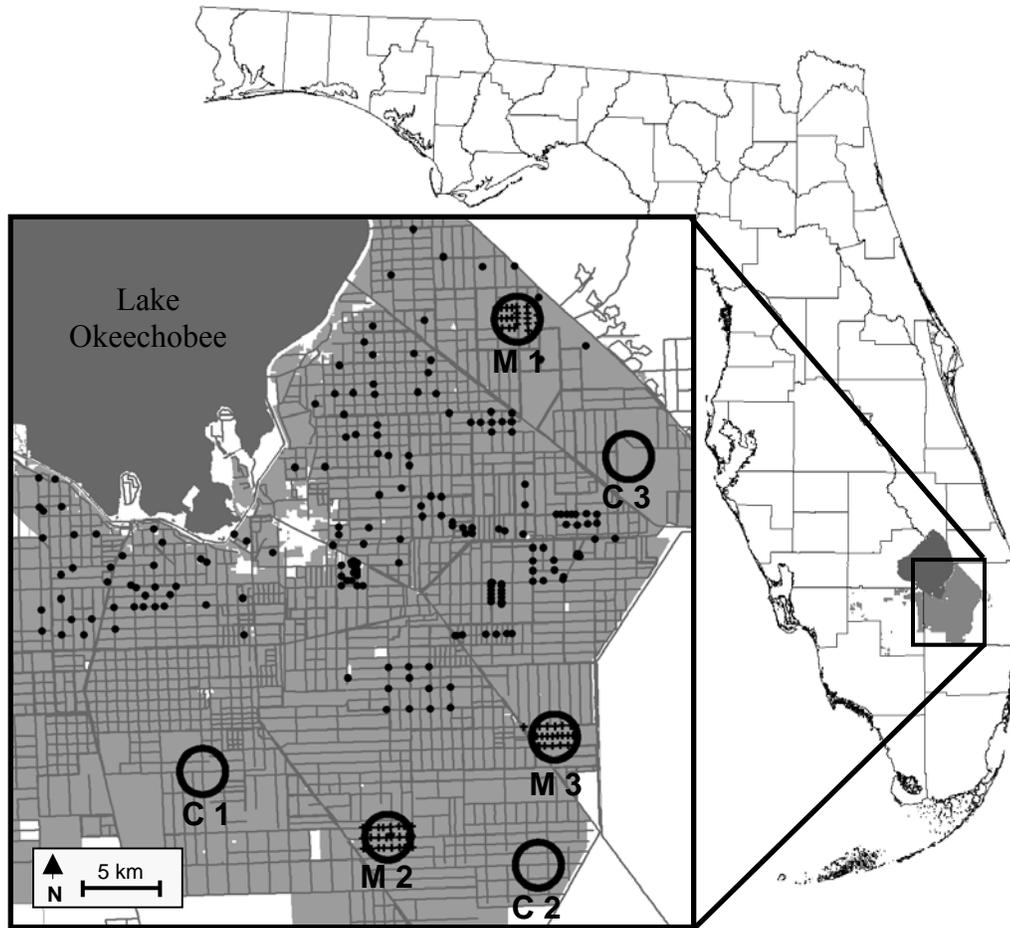
Figure 3-1. Everglades Agricultural Area and locations of sites used for experimental manipulation (M1, M2, M3) and control (C1, C2, C3). Dots represent Barn Owl nest boxes installed prior to 2005, pluses represent boxes installed at the end of 2005 for this study.
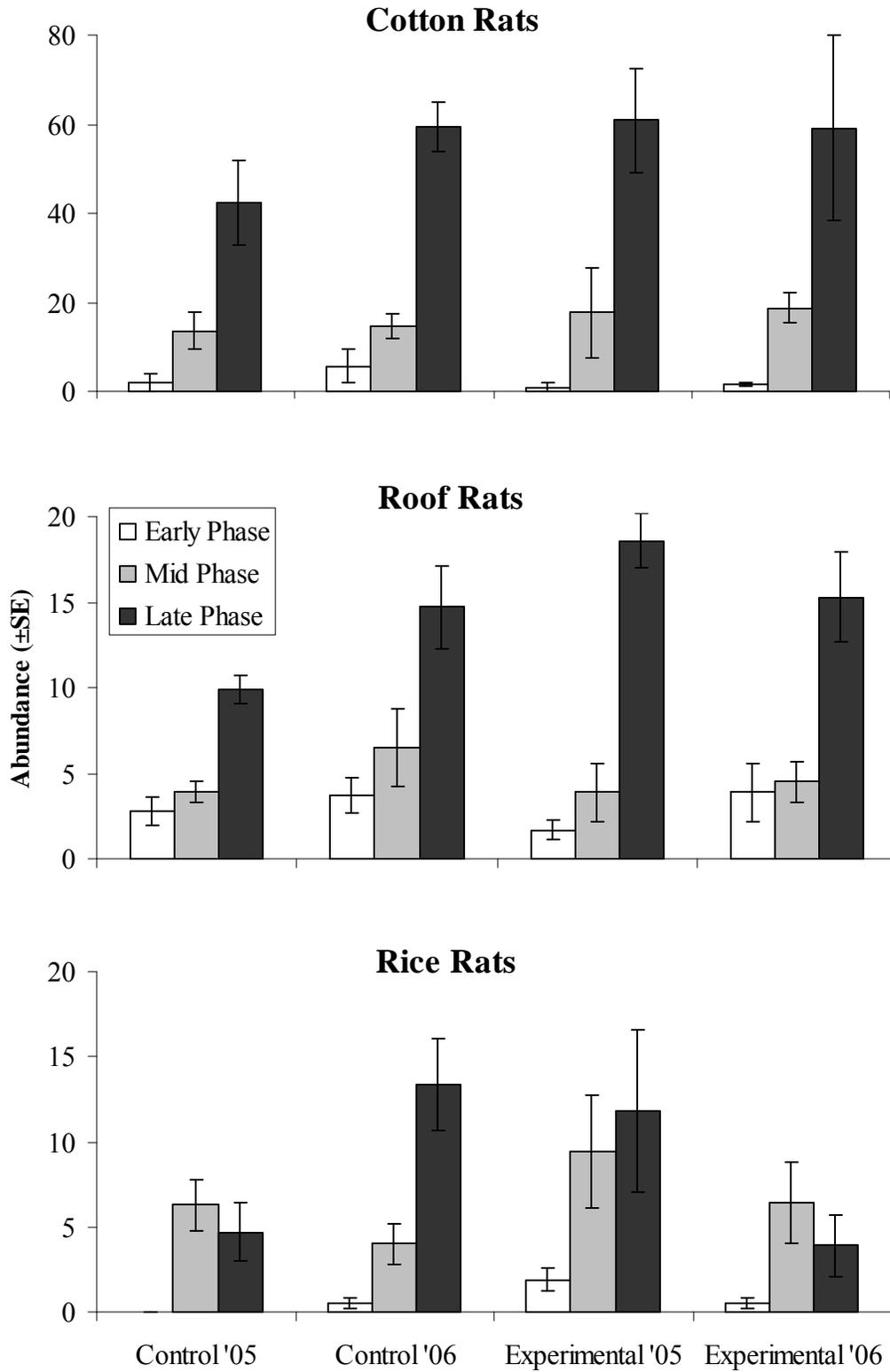
Figure 3-2. Mean abundance estimates (±SE) for cotton rats, roof rats, and rice rats derived from Huggins closed capture modeling using Program MARK.
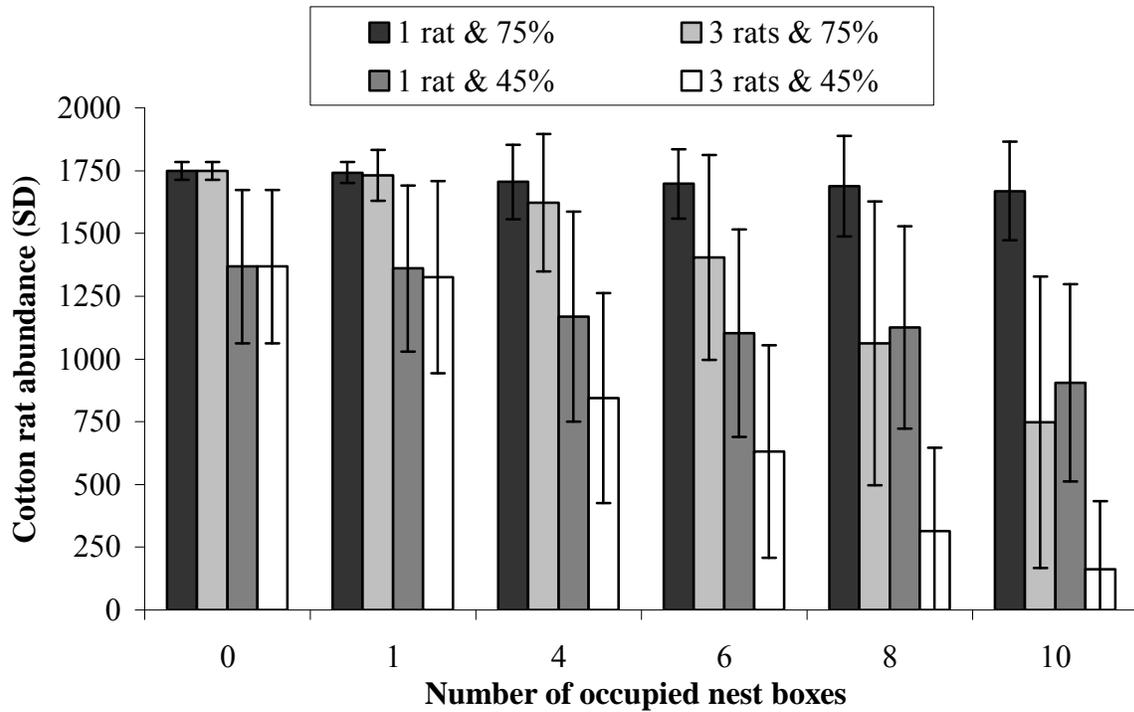
Figure 3-3. Peak abundance estimates of cotton rats in a single sugarcane field derived from PVA model scenarios simulating various densities of occupied Barn Owl nest boxes with two levels of predation intensity (1 & 3 rats consumed per owl per month) and two levels of cotton rat reproductive rates (75% and 45% of females breeding). Asterisk below bar indicates a significant difference ($p < 0.05$) from the reference estimate derived from the scenario with no nest boxes.

CHAPTER 4
NEST BOXES, BARN OWLS, AND AGRICULTURE: DOES CROP HARVEST LEAD TO
LOWERED REPRODUCTIVE SUCCESS?

Introduction

Avian species select habitat and nesting locations based on an assessment of habitat

quality (Petit and Petit 1996; Muller et al. 1997; Martin 1998; Kolbe and Janzen 2002).

Anthropogenic changes to habitat may cause environmental cues used by birds to assess quality

to no longer provide an accurate gauge of habitat suitability (Misenhelter and Rotenberry 2000;

Schlaepfer et al. 2002; Battin 2004; Weldon and Haddad 2005). An integral component of

habitat suitability is temporal stability. Organisms must predict long-term suitability of habitat

based on an immediate assessment of quality and do not have the ability to reject good habitat

that will be altered in the future. Temporal instability in habitat quality may be especially

consequential when selecting breeding sites (Orians and Wittenberger 1991). For example,

grassland birds often establish nests in croplands because the structure of these systems mimics

that of natural grassland habitat and because of the ample food supplies available in these areas.

However, nests in croplands often are destroyed by harvesting activities (Best 1986; Bollinger et

al. 1990). The decoupling of cue, quality, and temporal stability of habitat can lead to lowered

reproductive success of individuals, complete failure of nests, and extirpation of populations

(Kokko and Sutherland 2001; Shochat et al. 2005).

Nest boxes are useful tools for expanding nest site availability for many cavity nesting

bird species (e.g., Willner et al. 1983; Barry 1992). However, birds may be drawn to low quality

sites by poorly placed boxes (e.g., Semel and Sherman 2001). Furthermore, boxes may be

placed in areas that are considered by humans to be high quality based on an immediate

assessment of surrounding habitat, but these sites may lack the temporal stability of resources

required by the targeted species. Provision of artificial nesting structures may have negative

consequences if the wider ecological context of this management action is not fully considered.

Barn Owls (*Tyto alba*), which primarily are cavity nesters, occur in grasslands,

agricultural fields, and other open habitat throughout most of the world (Marti 1992; Taylor

1994). This species is declining throughout North America because of habitat alteration and

changes in agricultural practices (Taylor 1994). In the Everglades Agricultural Area (EAA) of

south Florida, where sugarcane is the primary crop grown, abundance of Barn Owls historically

has been limited because trees large enough to contain hollow spaces suitable for nesting are not

common and buildings used by owls for nesting and roosting are disappearing rapidly because of

hurricanes and general disuse. Over the past 20 years, approximately 200 Barn Owl nest boxes

have been installed throughout the EAA to enhance the regional owl population with the intent

of these raptors serving as biological controllers of pest rodents. At least two-thirds of the boxes

are used by owls during the nesting season (late Aug – June), and all appear to have been used

for nesting at least once (Martin, pers. obs.). Localized densities in the EAA can reach 18 pairs/5

km^2 (Martin, pers. obs.), whereas densities in other parts of this species' distribution range from

0.7 pairs/5 km^2 to 2.6 pairs/5 km^2 (Taylor et al. 1988; Altwegg et al. 2003).

The objective of this study was to assess nesting success of the Barn Owl population in

the EAA in relation to sugarcane harvest to determine if the temporal instability of the

agricultural landscape may lead to lowered reproductive success. At the time when most owl

nests are established, most of the sugarcane in EAA has not been harvested and rodents that

occupy crop fields are a plentiful food resource for owls. However, nesting chronology of Barn

Owls is relatively long (approximately 90 days; Marti 1992) and food availability declines

precipitously following harvest at some point during most nesting attempts (Chapter 3). I

hypothesized that crop harvest surrounding occupied nest boxes would result in lowered nest survivorship. I predicted that in areas where sugarcane was harvested before chicks fledged, chicks would exhibit lower rates of growth than chicks in areas that retained sugarcane. I also examined nest survivorship in relation to the proximity of major roadways because roadkill mortality of parental adults may serve as a secondary source of nest failure in the EAA (Martin, pers. obs.).

Research Design

I hypothesized that the daily survival rate of Barn Owl nests in the Everglades Agricultural Area would be lower after harvest of sugarcane. To test this hypothesis, I used a comparative observational approach. Active Barn Owl nest boxes were monitored throughout the nesting season and daily survival rates were calculated for pre- and post-harvest periods and nesting phases. I predicted that daily survival would be lower following harvest of all sugarcane fields adjacent to nest boxes and that the hatchling phase of nesting would have a lower daily survival rate than the incubation phase. I assumed that periodic observations of nests did not influence the fate of nests. Prior studies have indicated that the risk of observer-induced nest failure is minimal for this species, however I conducted nest visits at weekly intervals to further minimize this risk. Alternatively, daily survival of Barn Owl nests could have been influenced by date, age of nest, proximity of nests to well-traveled roadways, and climate (specifically temperature and rainfall). To test for these scenarios, I constructed a variety of predictive models of daily survival of Barn Owl nests and compared them using AIC.

I also hypothesized that the daily survival rate of individual Barn Owl chicks would be lower when nests are surrounded entirely by harvested fields than when there is at least one field with standing sugarcane nearby due to the crash in rodent abundance that follows sugarcane harvest. To test this hypothesis, I used a comparative observation approach. I calculated daily

survival for individual chicks from nests that either were or were not surrounded by standing

sugarcane fields for the entire nesting period. I also measured and compared the growth rate of

these chicks (mass, tarsus length, wing chord length). I predicted that the daily survival of

chicks in nests surrounded by harvested fields would be lower than those in nests with at least

one adjacent field with standing sugarcane. I also predicted that chicks that died before fledging

in post-harvest nests would have a slower rate of growth than chicks in pre- or post-harvest nests

that survived. I assumed that periodic observations of nests and handling of chicks did not

influence fate of the chicks. I conducted nest visits and measured chicks at weekly intervals to

minimize this risk. Alternatively, daily survival of Barn Owl chicks could have be influenced by

hatch order or age of chick. To test for these scenarios, I constructed a variety of predictive

models of daily survival of Barn Owl chicks and competed them using AIC.

Methods

Study location and species: The Everglades Agricultural Area is an approximately

160,000-ha region located in south Florida (Fig. 4-1). Sugarcane is the primary crop grown in

this area. Individual sugarcane fields, measuring 200 x 800 m, are harvested from Nov - Mar

following a 10 - 14 month growing season. Harvest occurs in a patchwork manner, with only a

few adjacent fields harvested simultaneously. As harvest progresses, the EAA landscape

becomes an increasingly sparse patchwork of standing sugarcane. Rodents are abundant in

sugarcane fields during most of the year (Holler et al. 1981; Lefebvre et al. 1989; Martin et al.

2007). However, rodents do not remain in fields following harvest and regional rodent

abundance likely drops greatly during this period resulting in an annual population cycle driven

by the cropping cycle (Chapter 3).

Barn Owls lay 4 – 7 eggs per nest (Marti 1992; Taylor 1994). Eggs are laid every 2 – 3

days until clutches are completed, but incubation begins after the first egg is laid. This results in

asynchronous hatching, which begins approximately thirty days following the onset of incubation. A developmental lag between younger and older chicks within broods remains evident until fledging occurs approximately 60 days after hatching. If nesting attempts are completed or fail early in the season, second nesting attempts can occur.

Monitoring overall nesting success: I monitored 93 active Barn Owl nest boxes in the EAA from 1 Dec 2004 – 31 Jan 2007, over 801 nest check intervals and 7231 exposure days. Most nests initiated before Nov 1 during the 2005 – 2006 nesting season were destroyed by Hurricane Wilma, therefore only nests initiated after this date were included from that nesting season. Approximately every 7 days, box contents were inspected visually or by using a video camera system mounted on the end of an extendable pole. If one egg was present following a check with no eggs, the nest was not checked for two weeks to minimize risk of nest abandonment. Following this, I visited active nests weekly until broods either fledged or failed and counted the number of eggs and/or chicks present during each visit. Nests were considered successful if at least two chicks survived to the expected fledging date for the nest, which was calculated as 60 days from the hatch date of the middle chick. I considered two chicks as the threshold for success, as opposed to one, because mortality for Barn Owls in their first year typically is high (Schifferli 1957; Frylestam 1972; Juillard and Beuret 1983). Number of days since the previous check and age of nest also were recorded during each visit. Mean temperature and total rainfall for each check interval were obtained from the Florida Automated Weather Network station at the Everglades Research and Education Center, Belle Glade, FL.

Monitoring within-nest survivorship: In order to examine the relationship between sugarcane harvest and within-nest patterns of mortality, I monitored the fates of 84 chicks in a subset of 18 nests. Eleven "post-harvest" nests, monitored from 7 Jan – 23 May 2006, were

selected in areas where all sugarcane fields within 1500 m of each nest box were harvested prior to nest initiation. This distance represents the approximate size of a Barn Owl home range (Hegdal and Blaskiewicz 1984; Marti 1992; Taylor 1994). Seven "pre-harvest" nests, monitored from 30 Aug – 22 Dec 2006, were selected in areas where harvesting activities in fields within 1500 m did not commence until after nests were completed. All nests were monitored following the previously described protocol; however, they were visited more frequently around the estimated hatch date (30 days from lay date; Marti 1992) in order to mark individual chicks. Colored nail polish was applied to talons of newly hatched chicks to facilitate identification of individuals. Once tarsi were fully developed (approximately 30 days), uniquely numbered USFWS lock-on leg bands were applied. After all chicks within a brood were marked, I checked nests weekly until they failed or fledged. During each visit, I recorded age, mass, tarsus length (tibio-tarsal articulation to palm), and wing chord (wrist to tip of unflattened, closed wing) for each nestling.

Habitat assessment: I assessed habitat around nests to examine the influence of sugarcane harvest on nest survivorship. I plotted the coordinates of all nest boxes onto a map of the EAA agricultural fields using ArcMap 9.2 (ESRI Inc., 2006). Crop type (sugarcane, rotational, or fallow) and harvest date of individual sugarcane fields were obtained from landowners. I then created individual field maps for each year of the study that described landcover and harvesting chronology. Only fields with standing sugarcane were considered suitable sources of prey for owls. Rotational crops (e.g., sod, rice, sweet corn, leafy vegetables) and fallow fields were unlikely to harbor significant rodent populations because of lack of cover, the presence of standing water, a short growing season with frequent soil disturbance, and/or frequent application of rodenticides. I determined if at least one standing sugarcane field

occurred within an approximated home range distance of Barn Owls (1500-m radius; Marti 1992) around each box on each check date.

Vehicle strikes may be a significant source of mortality for owls in the EAA (Martin, pers. obs.). Therefore, I also determined whether at least one major road occurred within 1500 m of each nest box using the 2000 TIGER Florida roads line file (US Census Bureau). Roads described in the dataset as "Primary" or "Secondary," as well as those frequently used to access sugarcane mills, were considered major roads.

Statistical analysis: I used the logistic-exposure method (Shaffer 2004) in Proc GENMOD (SAS 2003) to model the influence of various predictor variables on the daily survival rate of 93 nests. Prior to analysis, I developed the following set of candidate explanatory models: (1) DATE (date of check); (2) NESTAGE (age of nest); (3) TEMPERATURE and RAIN; (4) PHASE (incubation or hatchling); (5) SUGARCANE (presence/absence of standing sugarcane within 1500 m of nest); (5) ROAD (presence/absence of major road within 1500 m of nest); (6) SUGARCANE and ROAD; (7) PHASE and SUGARCANE; (8) PHASE and ROAD; and (9) PHASE, SUGARCANE, and ROAD.

For the subset of nests in which fate of individual chicks was monitored, I modeled the daily survival rate for each chick during the nestling phase only by fitting logistic exposure models using Proc NLMIXED. Survival rates of chicks within nests are not independent from each other because all are exposed the same nest-wide stressors (e.g., poor parental condition). Therefore, NEST was included as a random variable in all models. I developed the following *a priori* predictive model set: (1) ORDER (order that chick hatched within brood); (2) AGE (age of chick); (3) HARVEST (pre- or post-harvest); (4) AGE and HARVEST; (5) ORDER and HARVEST; (6) ORDER and AGE; (7) HARVEST*AGE; (8) ORDER*AGE; (9) HARVEST

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and ORDER*AGE; and (10) ORDER and HARVEST*AGE. I was unable to include the interaction of HARVEST and ORDER in the model set because of insufficient data. Number of siblings was not included in the analysis because all brood sizes were similar ($\bar{x}$ = 4.9, SE = 0.2).

I verified the fit of the most parameterized model for each dataset using the Hosmer-Lemeshow goodness-of-fit test (Hosmer and Lemeshow 2000). I used Akaike's information criterion (Burnham and Anderson 2002) to rank competing models. Best models were selected by judging degree of support as measured by ΔAIC_c and normalized Akaike weights. Models with $\Delta AIC_c \leq 2$ were considered competitive. To account for uncertainty in model selection, I also calculated model-averaged weighted parameter estimates and their associated standard errors and 95% confidence intervals (Burnham and Anderson 2002, Shaffer 2004). I then used these values to calculate odds ratios and their associated 95% confidence intervals. Odds ratios provide a direct interpretation of the influence of a variable on nesting success (e.g., Peak et al. 2004, Lloyd and Martin 2005). Odds ratio values greater than one indicate a positive effect and those less than one indicate a negative effect. If the 95% CI of the ratio encompasses one, no significant effect is indicated. I estimated daily survival rates for each level of explanatory variables that had significant odds ratios using the range of observed values of the covariates, while holding all other covariates in the models constant (Shaffer and Thompson 2007).

To examine the influence of sugarcane harvest on morphological development of chicks, I first divided the chicks into 4 groups: pre-harvest survived (n=23), pre-harvest died (n=5), post-harvest survived (n=28), and post-harvest died (n=28). Because sample size for pre-harvest chicks that died before fledging was small, I eliminated this group from the analysis. I then used a repeated measures approach in Proc Mixed (SAS) with NEST and AGE as random variables to compare mass, tarsus length, and wing chord among the three remaining groups. Appropriate

covariance structures were selected using best fit statistics. Data from the two groups that survived to fledge were truncated to the maximum observed age of post-harvest chicks that died (54 days) to facilitate comparisons among groups. I used Bonferroni adjusted p-values to perform pair-wise comparisons among groups. This multiple-comparison correction is a more conservative approach than using standard p-values (Wright 1992).

Results

Twenty-two of the 93 nests (24%) failed. Eighty-two nests (88%) were established in nest boxes that were surrounded primarily by unharvested sugarcane fields at the time of nest initiation. Of these, sugarcane was removed entirely within 1500 m of 53 nests and was partially removed within 1500 m of 29 nests at some point during nesting. Eleven of the 93 nests (12%) were established in nest boxes after all sugarcane fields within 1500 m had been harvested. At least one major road occurred within 1500 m of fifty-eight nests (62%).

Overall reproductive success: The most parameterized model adequately fit the observed values for overall nesting success ($\chi^2 = 3.88$, df = 6, P = 0.69). The model that contained independent effects of PHASE, ROAD, and SUGARCANE received the strongest support (Table 4-1). No other models were competitive. The confidence interval for the odds ratio of SUGARCANE indicated significance, and the odds ratio value suggested that the odds of a nest surviving from one day to the next was about 4 times higher when sugarcane was present within 1500 m of a nest than when it was absent (Table 4-2, Fig. 4-2A). There was a trend towards a lower daily survival rate during the hatchling phase than during the incubation phase, but this trend was not significant (Table 4-2, Fig. 4-2B). There also was a trend towards lower daily survival when major roads were near nests than when they were absent, but likewise this trend was not significant (Table 4-2, Fig. 4-2C).

Within-nest survivorship: The most parameterized model adequately fit the observed values for within-nest survivorship ($\chi^2 = 5.22$, df = 7, P = 0.63). The model containing the effect of ORDER and the interaction of HARVEST and AGE received the strongest support (Table 4-3). No other models were competitive. Although the model averaged parameter estimate for ORDER was not significant (Table 4-4), this parameter was a significant factor ($p < 0.05$) in all individual models in which it was included. The interaction between HARVEST and AGE was significant (Table 4-4). Daily survival rate increased slightly with age in nests surrounded by sugarcane and decreased with age in nests surrounded by harvested fields (Fig. 4-3). Overall, daily survival appeared to be higher in nests surrounded by standing sugarcane, but was highly variable in nests surrounded by harvested fields.

Morphological development: Mass of individual chicks varied significantly depending on whether they were from nests prior to harvest and survived to fledge, were from post-harvest nests and survived, or were from post-harvest nests and died before fledging (F = 4.26, df = 2, p = 0.01; Fig. 4-4). Post-harvest chicks that died during nesting weighed significantly less than pre-harvest chicks and post-harvest chicks that survived to fledge (t = -2.56, pBonf = 0.03; t = -2.44, pBonf = 0.04, respectively). Mass did not differ between pre-harvest and post-harvest chicks that survived (t = -0.46, pBonf = 1.94). Tarsus length varied significantly among groups as well (F = 3.76, df = 2, p = 0.02), however this was not reflected in the Bonferroni pair-wise comparisons. Wing chord did not vary significantly among any groups (F = 1.24, df = 2, p = 0.29).

Discussion

Abundance of rodents in the EAA is linked to the annual cropping cycle of sugarcane (Chapter 3). Prior to harvest, rodents are extremely abundant within individual fields. Rodent populations crash following the removal of food and cover resources via harvesting activities,

and then increase throughout the following year as new sugarcane crops mature, and the food and cover that they provide for rodents is restored. Nesting success of some Barn Owls in the EAA clearly was negatively influenced by sugarcane harvest, likely because of harvest-induced crashes in their primary food source during nesting.

Overall daily survival rate of owl nests was significantly lower after sugarcane adjacent to nests was removed. However, daily survival rates for nests were highly variable when sugarcane was absent. This variability may have been attributable to habitat characteristics not measured in this study, such as the presence of weedy ditch banks and refuse piles. These areas may serve as refugia habitats that allow rodents to persist locally following sugarcane harvest. Another potential source of this variability was variation in parental hunting ability, which may not have become apparent until food resources were relatively scarce in the landscape. The survivorship of individual chicks in nests surrounded by sugarcane was higher than that of chicks in nests where adjacent sugarcane had been completely harvested. Although monitoring of pre- and post-harvest nests was confounded with time, abundance of rodents in fields adjacent to nests was more likely to be associated specifically with the presence or absence of food and cover in those fields rather than with date in general.

When sugarcane was absent and rodents likely were scarce in the vicinity of nests, daily survival rate of chicks decreased with age. For birds in general, the likelihood of daily survival typically increases with nest age during the nestling phase (e.g., Dinsmore et al. 2002; Grant et al. 2005). Nearly all of the chicks from nests surrounded by sugarcane for which I monitored morphological development survived to fledge. Conversely, half of those from nests where sugarcane had been harvested died during nesting. Chicks that died before fledging from nests where sugarcane had been harvested weighed less than all chicks that survived to fledge. This

suggests that lower survivorship following harvest was attributable to diminished food resources during this period. Although some hatchling mortality may have been linked to parental mortality associated with roads, starvation likely was the primary source of hatchling mortality. A similar pattern of Barn Owl chick survivorship has previously been linked to vole cycling (~95% of chicks fledged during peak vole years, ~55% fledged in vole decline years; Taylor 1994).

When most Barn Owls in the EAA select nesting locations, the entire landscape could be considered "good" because harvesting activities have not begun and therefore food resources are plentiful and widely distributed. The limiting factor of owl density at this time likely is nest site availability. The provision of nest boxes may enable the EAA owl population to exist at an extremely high density with breeding owls being very fecund if food availability remains stable over time. However, when harvesting begins and rodent populations decline, as occurs around almost all of the owl nests in the EAA to some degree, the system shifts towards an undesirable condition. By this point, owls are locked into nesting locations and they may experience an ecological trap that is temporal in nature. I did not collect long-term demographic data to test for population level effects, however this study shows that a mechanism for a trap exists in the form of temporal instability of habitat quality. Trap mechanisms that are spatial or behavioral in nature are well documented (Schlaepfer et al. 2002), however traps resulting from temporal shifts of habitat quality within breeding seasons are not. When evaluating how habitat variables influence nesting success of birds, and ultimately how these factors influence populations of birds as a whole, it is imperative to consider how the influence of habitat may shift over time.

A highly productive population of Barn Owls in the EAA may contribute to the stability of the wider regional population by providing recruits that disperse throughout the surrounding

landscape. Young owls produced in the EAA may be capable of spreading throughout the southeastern United States into areas where the species is imperiled. Little is known about dispersal patterns of juvenile Barn Owls, but dispersal distances of up to 2000 km have been recorded (Stewart 1952, Soucy 1980). This topic merits further study to determine the extent to which metapopulation dynamics may exist for this species. Meanwhile, efforts should be made to maximize the reproductive output of Barn Owls in the EAA. This may be achieved by simply delaying harvest of sugarcane fields adjacent to active nest boxes until after nesting has been completed.

Table 4-1. Model-fit for nest success analysis of 93 Barn Owl nests in the Everglades Agricultural Area, 2004-2007.

Model	K	AIC_c	ΔAIC_c	w_i
PHASE + ROAD + SURGARCANE	4	179.13	0.00	0.747
ROAD + SURGARCANE	3	182.79	3.66	0.120
PHASE + SURGARCANE	3	183.37	4.25	0.089
PHASE + ROAD	3	186.34	7.21	0.020
SURGARCANE	2	186.44	7.31	0.019
DATE	2	191.90	12.78	0.001
PHASE	2	192.01	12.88	0.001
TEMPERATURE + RAIN	3	192.60	13.47	0.001
ROAD	2	195.66	16.53	0.000
NEST_AGE	2	198.10	18.97	0.000
CONSTANT	1	200.51	21.38	0.000

Table 4-2. Model-averaged parameter estimates and odds ratio values of predictor variables of Barn Owl nest success in the Everglades Agricultural Area, 2004-2007.

Variable	Model-averaged parameter estimate	SE	Odds ratio	95% CI
SURGARCANE (Present vs. Absent)	1.46	0.56	4.29	1.42-13.01
PHASE (Incubation vs. Hatchling)	1.29	0.86	3.64	0.65-20.37
ROAD (Absent vs. Present)	1.19	0.70	3.29	0.81-13.40
DATE	0.00	0.00	1.00	1.00-1.00
NESTAGE	0.00	0.00	1.00	1.00-1.00
RAIN	0.00	0.00	1.00	1.00-1.00
TEMPERATURE	0.00	0.00	1.00	1.00-1.00

Table 4-3. Model-fit for analysis of survival of 84 individual Barn Owl chicks in the Everglades Agricultural Area.

Model	K	AIC_c	ΔAIC_c	w_i
ORDER + HARVEST*AGE	6	186.73	0.00	0.990
HARVEST + ORDER*AGE	6	198.48	11.74	0.003
ORDER + AGE + HARVEST	5	198.55	11.81	0.003
ORDER + AGE	4	198.64	11.91	0.003
ORDER*AGE	5	198.90	12.17	0.002
HARVEST*AGE	5	212.87	26.13	0.000
ORDER + HARVEST	4	214.17	27.44	0.000
ORDER	3	214.82	28.09	0.000
AGE + HARVEST	4	219.77	33.04	0.000
AGE	3	221.27	34.54	0.000
HARVEST	3	222.90	36.17	0.000
CONSTANT	2	224.45	37.72	0.000

Table 4-4. Model-averaged parameter estimates and odds ratio values for predictor variables of survival of 84 individual Barn Owl chicks in the Everglades Agricultural Area.

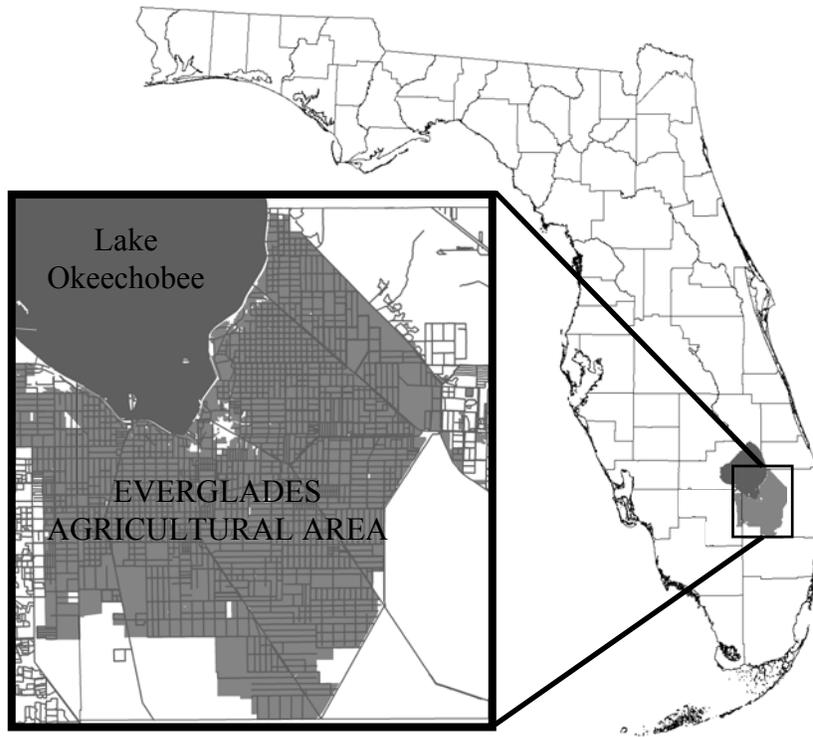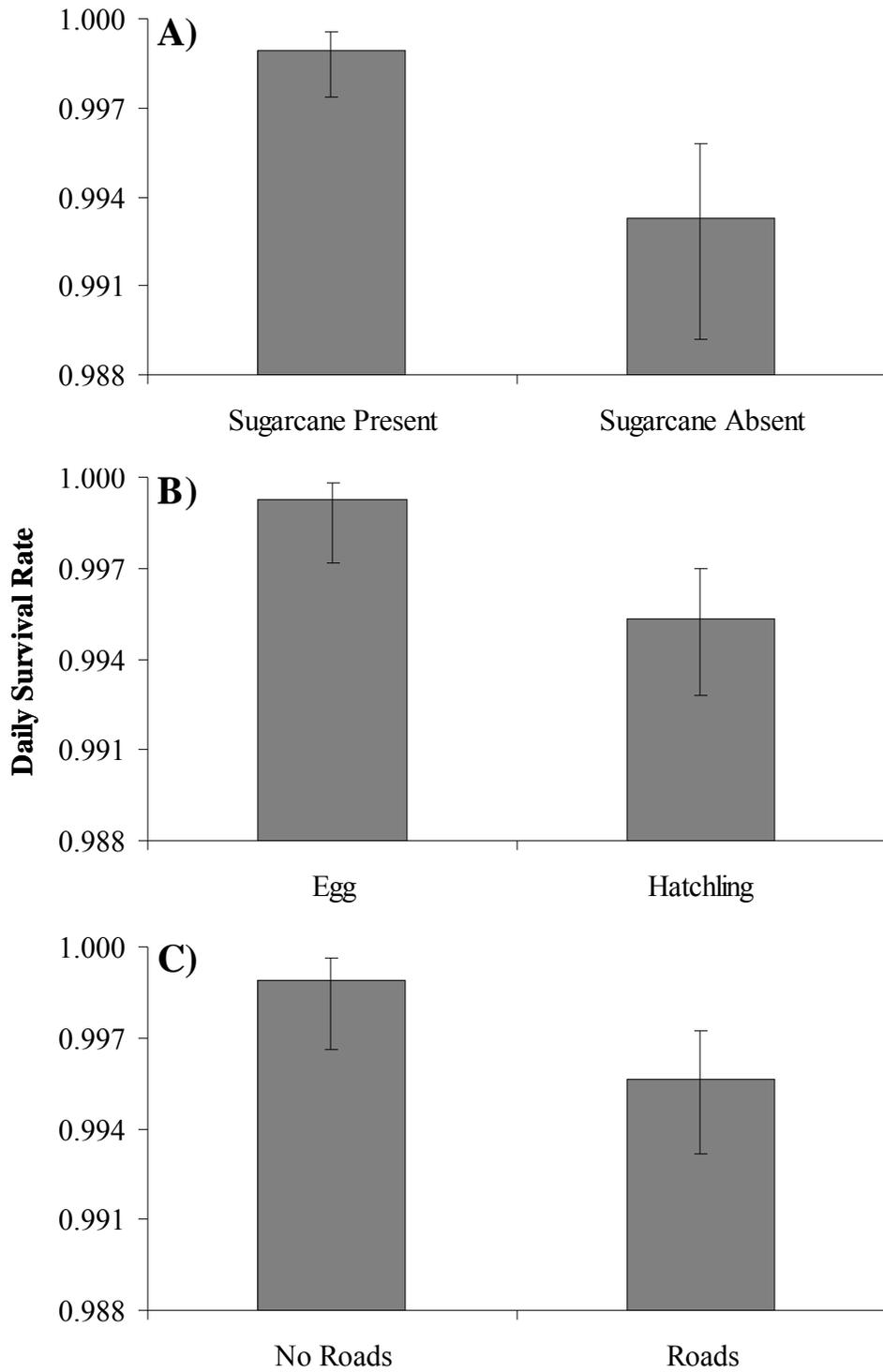| Variable	Model-averaged parameter estimate	SE	Odds ratio	95% CI
ORDER	-1.03	0.24	0.36	1.27-0.22
AGE	-0.10	0.02	0.90	1.02-0.86
HARVEST (Post- vs. Pre-harvest)	-2.80	1.68	0.06	5.35-0.00
ORDER*AGE	0.00	0.00	1.00	1.00-1.00
HARVEST*AGE (Post- vs. Pre-harvest)	0.12	0.04	1.13	1.04-1.05

Figure 4-1. Location of the Everglades Agricultural Area.

Figure 4-2. Daily survival rates (±95% CI) for Barn Owl nests (A) when sugarcane was present and absent within 1500 m, (B) during incubation and hatchling nest phases, and (C) when roads were present or absent within 1500 m
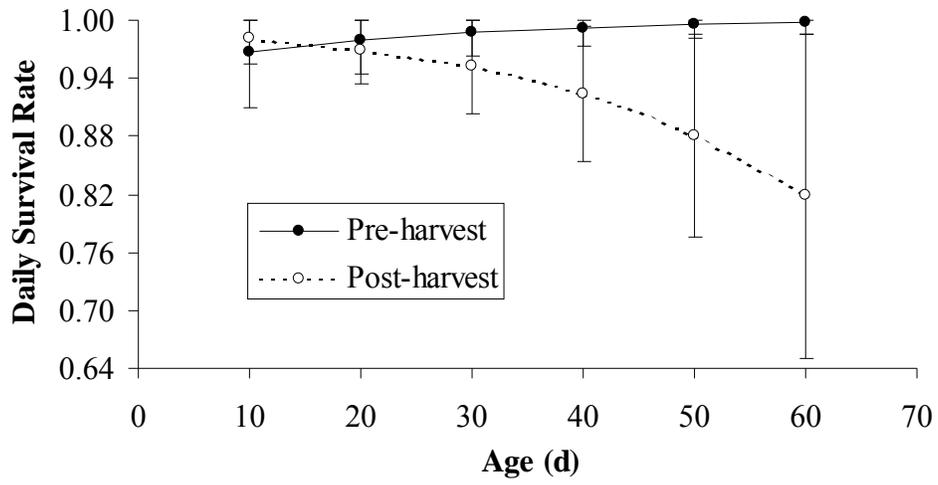
Figure 4-3. Daily survival rates (±95% CI) of individual Barn Owl chicks by age of chick when sugarcane was present and absent.
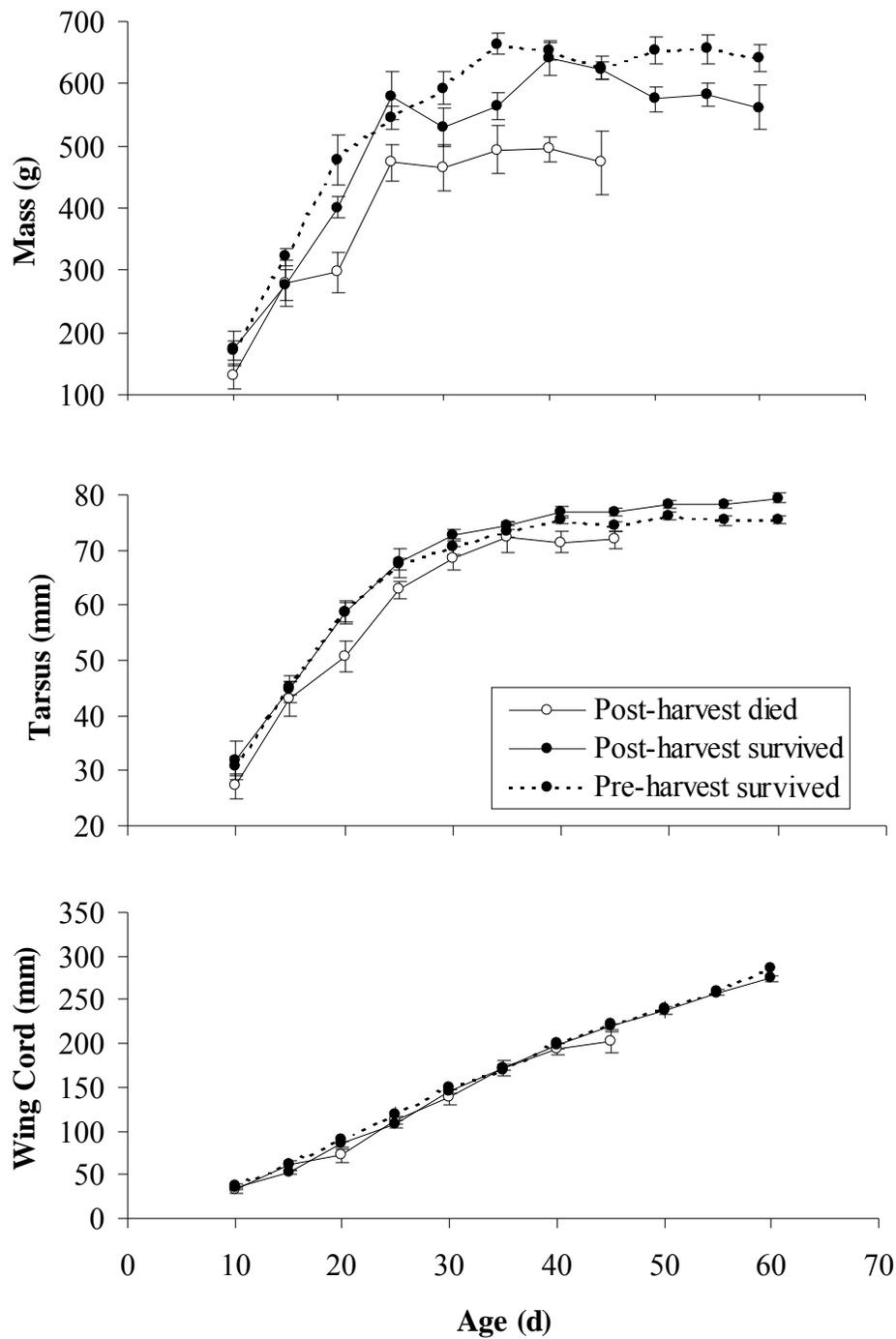
Figure 4-4. Growth curves depicting mean mass, tarsus length, and wing chord length (±SE) for Barn Owl nestlings.

CHAPTER 5
CONCLUSION

Barn Owls in the EAA prey heavily on cotton rats, roof rats, and rice rats. However, the results of this study do not indicate that Barn Owls are capable of reducing abundance of these crop pests. Reproductive capacity of all three species of rodent likely far exceeds rate of removal of individuals from the population via predation. Cotton rats are capable of producing litters of 10-15 young every month throughout the year, and roof rats and rice rats are only slightly less fecund (Whitaker and Hamilton 1998).

Rodent populations occur at the scale of landscapes, but owl predation is a relatively localized phenomenon restricted primarily to areas near active nests for most of the year. Depredated rodents within foraging ranges of owls likely are replaced continually by dispersing individuals from the surrounding landscape. Increasing density of Barn Owls across the EAA at the scale required to reduce regional rodent abundance is not feasible. The threshold of owl density required to produce a measureable decline in rodent populations is unobtainable high. Further studies are needed to determine if Barn Owl predation can reduce rodent abundance if combined with other pest control techniques, such as strategically timed application of rodenticides and elimination of rodent refugia habitat following harvest, in an integrated pest management approach.

Abundance of rodents in the EAA is linked to the annual cropping cycle of sugarcane. Prior to harvest, rodents are extremely abundant within individual fields. Rodent populations crash following the removal of food and cover resources via harvesting activities, and then increase throughout the following year as new sugarcane crops mature, and the food and cover that they provide for rodents is restored. The survivorship of both nests and individual chicks

was higher before sugarcane was harvested when compared to post-harvest conditions, likely due to harvest-induced crashes in rodents, the primary prey of the owls.

In order for an ecological trap to exist, organisms must select poor-quality habitat over higher quality habitat and those organisms must suffer reduced fitness, potentially in the form of lowered reproductive output, as a result of this choice (Donovan and Thompson 2001; Robertson and Hutto 2006). In agricultural landscapes birds may not have a dichotomous choice of "good" vs. "bad" habitat because of the homogeneous nature of the landscape. For example, when most Barn Owls in the EAA select nesting locations, the entire landscape could be considered "good" because harvesting activities have not begun and therefore food resources are plentiful and widely distributed. The limiting factor of owl density at this time likely is nest site availability. The provision of nest boxes may enable the EAA owl population to exist at an extremely high density with breeding owls being very fecund if food availability remains stable over time. However, when harvesting begins and rodent populations decline, as occurs around almost all of the owl nests in the EAA to some degree, the system shifts towards an undesirable condition. By this point, owls are locked into nesting locations and they may experience an ecological trap that is temporal in nature. I did not collect long-term demographic data to test for population level effects of an ecological trap, however this study shows that a mechanism for a trap exists in the form of temporal instability of habitat quality. Trap mechanisms that are spatial or behavioral in nature are well documented (Schlaepfer et al. 2002), however traps resulting from temporal shifts of habitat quality within breeding seasons are not. When evaluating how habitat variables influence nesting success of birds, and ultimately how these factors influence populations of birds as a whole, it is imperative to consider how the influence of habitat may shift over time.

Although augmentation of owl density through installation of nest boxes does not appear to be an effective means of rodent control in large agricultural systems, this management tool may be important for conservation of owls as traditional nest sites of this species become scarce. As in previous studies (e.g., Muñoz and Murúa 1990; Lee 1997; Moore et al. 1998; Potter 2004), I found that Barn Owl density can easily be manipulated by installing nest boxes. However, the success of this management technique exhibited in this study may have been greater than that in other areas because of extremely high localized abundance of owls in the EAA. Nevertheless, although Barn Owl management programs involving nest boxes should not expect colonization to the degree achieved in the EAA, nest boxes are a proven management option where increasing abundance of the species is desirable.

A highly productive population of Barn Owls in the EAA may contribute to the stability of the wider regional population by providing recruits that disperse throughout the surrounding landscape. Young owls produced in the EAA may be capable of spreading throughout the southeastern United States into areas where the species is imperiled. Little is known about dispersal patterns of juvenile Barn Owls, but dispersal distances of approximately 2000 km have been recorded (Soucy 1980). This topic merits further study to determine the extent to which metapopulation dynamics may exist for this species. Meanwhile, efforts should be made to maximize the reproductive output of Barn Owls in the EAA. This may be achieved by simply delaying harvest of sugarcane fields adjacent to active nest boxes until after nesting has been completed.

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BIOGRAPHICAL SKETCH

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