The Big Brown Bat (*Eptesicus fuscus*) and the Little Brown Bat (*Myotis lucifugus*) as a Biological Pest Control for the Adult Female Codling Moth (*Cydia pomonella*) in Illinois Apple Orchards

By
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The Benefit Obtained by Incorporating the Big Brown Bat (*Eptesicus fuscus*) and Little Brown Bat (*Myotis lucifugus*) as a Biological Pest Control for the adult female Codling Moth (*Cydia pomonella*) on Illinois Apple Orchards

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Abstract

Apple orchard famers have difficulty producing a market-accepted product without heavy use of insecticides to control apple orchard pest insects. Sustainable agricultural methods enable naturally beneficial processes to arise, generating both economic and environmental benefits. Integrated pest management (IPM) is one method of sustainable agriculture that incorporates the use of chemical and biological methods to control agricultural pests. Insectivorous bats are often overlooked as a biological arthropod predator. The big brown bat (*Eptesicus fuscus*) and the little brown bat (*Myotis lucifugus*) are of the most populous and distributed bat species in North America which can be attributed to their ability to utilize man-made structures and their relative disregard for human disturbance. These attributes make these natural pest predators an easily recruited aspect of an IPM strategy.

The most loathed apple orchard pest is the codling moth (*Cydia pomonella*). *E. fuscus* and *M. lucifugus* have the capacity to be a substantial suppressant of *C. pomonella*'s adult form because, like both bat species, it is most active around sunset. Through the examination of published research, *E. fuscus's* and *M. lucifugus's* diet compositions were evaluated by determining percent volume of each insect order consumed. This study specifically evaluates the consumption of adult female *C. pomonella* and the corresponding reduction of *C. pomonella* larvae which resulted from the consumption of adult female *C. pomonella* in an apple orchard. *E. fuscus*'s dietary inclination for beetles made it less effective as a suppressant of *C. pomonella* than *M. lucifugus*. *M. lucifugus's* diversified diet allowed consumption of *C. pomonella* at a higher rate than *E. fuscus* despite the larger body mass of *E. fuscus*. These findings suggest that the incorporation of bats into apple orchard pest management strategy holds potential environmental and economic benefit due to the potential of decreased pesticide applications.

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Introduction

Current conventional agricultural practices depend heavily on chemical fertilizers and pesticides (Gianessi and Reigner, 2006). Unfortunately, many of these have not produced the continued effective results despite increased applications and intensity, creating increased tolerance among pests exposed to the altered environment (Pimentel, 2005). The indiscriminate

use of pesticides has many unknown effects to humans, i.e. health, the economy and the environment (Chivian and Bernstein (1), 2008). By embracing agricultural methods that combine knowledge regarding plant's growing preferences, maintenance of soil integrity, interactions of naturally occurring pest insects and predators, and other ecologically based information, economic profit can be obtained. The inclusion of ecological principles into conventional agricultural is termed "integrated" agriculture (Chivian and Bernstein (1), 2008). Although implementing these methods can require initial investment, these more sustainable methods create benefits that persist long-term. Therefore, although not all sustainable methods may be feasible, possessing ecological understanding can allow for the implementation of the most easily achievable and valuable methods.

A sustainable agriculture system, also called integrated agriculture, aims to be mindful of and to develop in conjunction with the surrounding ecosystems (Chivian and Bernstein (1), 2008). Sustainable practices allow natural processes to collectively and beneficially propel one another, maintaining the integrity of nutrient, predatory, and other ecological cycles. Many agrarian communities unknowingly utilize what is considered small-scale organic agriculture practices as these methods naturally promote the well being of farmed land by preserving the ecosystem services naturally provided by the Earth (Chivian and Bernstein (1), 2008). Ecosystem services are goods and services provided by separate or collective parts of an ecosystem that are vital to human's current state of life (USDA (1), 2011).

One often overlooked naturally persisting agricultural resource is bats as they provide many ecosystem services including arthropod suppression, pollination, seed dispersal, a food source, and the option of bat watching (Kunz et al. (1), 2011). However, these beneficial qualities are often muted by misconceptions of bats as "blood-suckers" and rabid (Nowak, 1994). It should be noted that of the three species of vampire bats, none of them reside north of southern Texas and their feeding is often non-detrimental to their host (Nowak, 1995). Similarly, between the years of 1995 and 2009 there is an average of 2 deaths per year associated with rabies transmitted by bats (Bat Conservation Trust, 2009). Therefore, it would be more advantageous to consider bats in relation to the ecosystems services they provide to the production of goods and services consumed by humans (Kunz et al. (1), 2011).

One component of integrated agriculture is integrated pest management, or IPM (EPA (1), 2011). IPM is a systems approach to pest management that utilizes quantitative or qualitative

observations of pests and their related ecological interactions (Willson, 1992). It is well-known that many bat species are voracious insect eaters; however, this characteristic has been greatly undervalued and minimally quantified within the agricultural sector of the economy (Kunz et al. (1), 2011). Although bats are often an overlooked asset in the agricultural sector, generating knowledge of their feeding preferences can allow their natural ravenous appetites to work for the benefit of agricultural practices.

Of the 12 Illinois bat species, the big brown bat (*Eptesicus fuscus)* and the little brown bat (*Myotis lucifugus)* are the most abundant, most successful in utilizing human development and demonstrate endurance in the presence of human disturbance (Agosta, 2002; Saunders, 1988). All bat species in Illinois are insectivorous; however, there is minimal understanding of their utilization of apple orchards' agricultural pests as a food source. This study seeks to quantify *E. fuscus'*s and *M. lucifugus'*s consumption of the codling moth *(Cydia pomonella)* and the associated environmental and economic values that are generated for Illinois apple orchards.

C. pomonella is the most threatening pest in apple orchards. Its larval stage is most destructive, burrowing into the core of the apple creating holes upon entry and exit. However, the control of its adult form acts as a defensive control measure, preventing the eggs from being laid and, in due course, larvae from hatching (Figure 1). This strategy holds potential since adult *C. pomonella* are, like bats, most active around sunset (Gharekhani, 2009).

Figure 1: Damage from *C. pomonella* entrance or exit into side and
calyx (bottom) of apple and frass remains from exit of apple

Since bats naturally exist in agricultural settings, their pest predation characteristics should be incorporated in agricultural IMP strategies since that has potential to be more economically and environmentally advantageous than continued use of synthetic insecticides (Cleveland et al., 2006; Williams-Guillen, 2008; Kalka, 2008). Through various changes to

traditional land management and agricultural practices, bats can become one of the working parts of a functional, efficient pest management strategy on apple orchards in Illinois.

This study was undertaken and completed using published studies' results, allowing the opportunity to gather more particular field research which would make the results and conclusions more characteristic of particular bat species or agricultural settings. This study has economic and environmental applications by providing a reference for future studies of economic gain from bats in agriculture through its analysis of the influence bats hold in agriculture. The incorporation of *E. fuscus* and *M. lucifugus* into Illinois apple orchard's IPM strategies will facilitate their consumption of *C. pomonella* which will decrease adult *C. pomonella*'s numbers, reduce the number of *C. pomonella* eggs due to the consumption of adult female *C. pomonella,* and ultimately prevent *C. pomonella* larvae, reducing damage to apples. Future research will investigate how the incorporation of *E. fuscus* and *M. lucifugus* could allow for the reduction of pesticide applications in apple orchards. Also, guidelines are provided to determine which bat research topics need further research and how further analysis of bat's ecosystem services has potential to generate wide-scale incorporation of bats into agricultural IPM strategies.

This study highlights characteristics that are most relevant to bat's ability as a biological pest control of *C. pomonella*. The characteristics that hold the most pertinence are body size and natural diet composition. Based on these characteristics, this study hypothesizes that both *M. lucifugus* and *E. fuscus* will provide economic benefit as a biological pest control of *C. pomonella* with *M. lucifugus* demonstrating a higher capacity than E. fuscus. *M. lucifugus*'s superior is derived from *E. fuscus's* dietary preference for insects in the order Coleoptera and relative exclusion of insects in the order Lepidoptera, i.e. *C. pomonella.*

Literature Review

History of Bat Research

Intrigue into the scientific study of bats began approximately 60 years ago. However, due to a lack of technology and the overall elusive nature of bats, a number of scientific inquiries had not been able to be completely determined. Recent technological developments, such as improved tracking, advanced lab techniques, and increased of knowledge related to bats habits

and morphology, have allowed the field to expand. Some of these technologies include the ANAbat and Echo Meter 3 (EM3), used in the passive monitoring of bats, and utilization of quantitative polymerase chain reaction (qPCR) in analysis of percent volume of prey species within bats' diet. Continued utilization of these and other technologies are allowing bat research to expand in scope and use the collected data to justify bat conservation efforts and education.

In order to supplement the lack of technology in the past, some scientists looked to species they considered comparable and studied them to infer habits of bat species such as migration and diet. For example, the literature on migration physiology of birds (e.g. Berthold, 1993; Gwinner, 1990; McWilliams et al., 2004, etc.) allowed researchers to model predictions about bat's migration physiology because, although taxonomically distinct, bats and birds are both endothermic vertebrates capable of flight and should therefore face similar selective pressures on their physiology in relation to flight and migration. Similarly, predictions were able to be made about bat's fuel acquisition and storage as well as fuel utilization by comparative analysis (McGuire and Guglielmo, 2009). Although this research gave insight into bat's physiological evolution, bats have unique features including reproductive allocation and feeding preferences, which were unable to be explained using this inquiry method. Therefore, persistent dedication to bat research continues to uncover the unique nature of bats.

The Academic Inquiry into Bats

Despite the unknowns of bat research, the entirety of bat research has provided substantial information pertaining to bat's morphology and ecological significance (Feldhamer et al. (1), 2007; Boyles et al., 2011, Kunz et al. (1), 2011, Cleveland et al., 2006, etc.). There are approximately 1,116 species of bat located within 18 families of the suborders Megachiroptera and Microchiroptera, in the order Chiroptera and in the class Mammalia (Feldhamer et al. (1), 2007). Reflecting the impressiveness of their sheer numbers, bats also demonstrate a higher degree of specialization than any other mammalian order when considering their feeding habits, reproductive behavior, and morphology (Feldhamer et al. (1), 2007).

Megachiropterans, which consist of one family containing approximately 186 species, are Old World fruit bats occurring throughout tropical and subtropical areas of the Old World. As the common name implies, they are generally frugivores or nectivores. They have a relatively large body size, despite some species being smaller than the Microchiroptera (Feldhamer et al.

(1), 2007). They generally do not echolocate which correlates with their absent tragus, lack of nose or facial ornamentation and generally large eyes. Their tail and uropatagium is usually absent (Figure 2) (Feldhamer et al. (1), 2007).
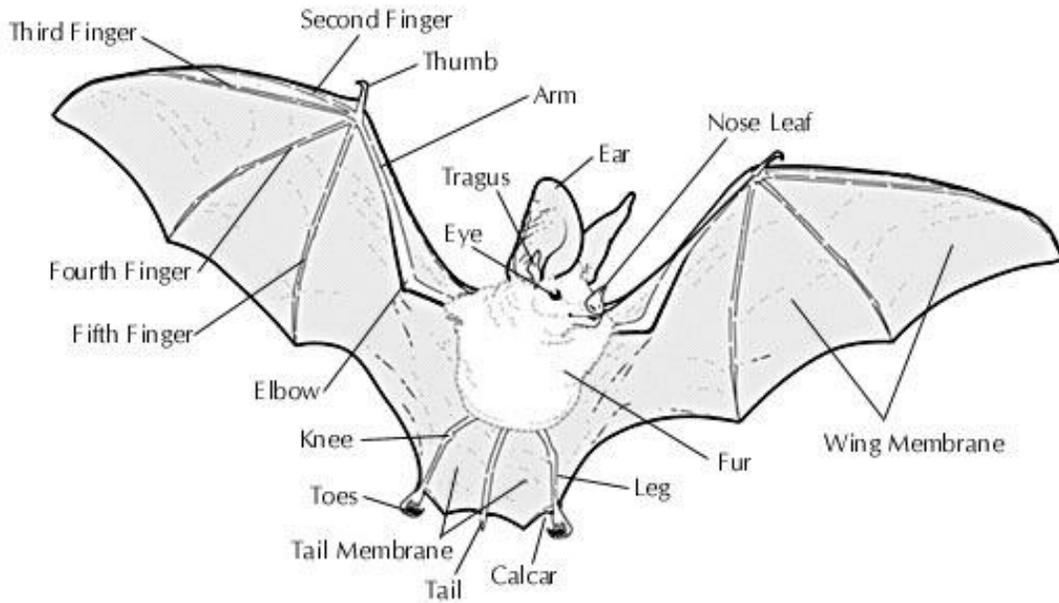

Figure 2: The basic external anatomy of generalized Microchiropteran.

Microchiropterans, which consist of the 17 other families of bats, comprised of approximately 930 species, are located in all parts of the world apart from the Arctic, Antarctic, and a few isolated oceanic islands (Bat Conservation Trust, 2011). These commonly small bodied bats are often referred to as "echolocating bats" because of their use of echolocation in obstacle avoidance, hunting and other forms of communication (Simmons and Tenley, 1997). They are primarily insectivorous although some eat frogs, bids, lizards, fish, blood, fruit, nectar and pollen. They often have a well-developed tragus, a nose or facial ornamentation, and small eyes, all of which correlate with their use of echolocation, or biosonar (Figure 2) (Feldhamer et al. (1), 2007). The two bats in this study, *Eptesicus fuscus* and *Myotis lucifugus,* are Microchiropterans.

Bat Morphology

With many of their most unique morphological features pertaining to flight, bats are the only mammals that are able to fly (Feldhamer et al. (1), 2007). The name Chiroptera is derived

from the Greek *chier* (hand) and *pteron* (wing), which refers to the modification of the bones in the hand into a wing which is the primary adaptation for flight in bats (Figure 2). The wing is formed from skin that is stretched between the arm, wrist and finger bones with several muscles groups keeping the skin stretched tightly over the wing (Feldhamer et al. (1), 2007) (Figure 2). The restriction of movement to a single plane, caused by modifications in the forelimb, gives the wing strength and rigidity to withstand air pressure associated with flight (Feldhamer et al., 2007). The wings also aid bats in thermoregulation by dissipating excess body heat generated during flight (Feldhamer et al. (1), 2007).

The uropatagium, sometimes referred to as the interfemoral membrane or tail membranes, is the membrane between the hind limbs that surround the tail (Diagram 1). This feature aids bat's flight by contributing to lift and stabilization during various maneuvers. Aerodynamic stability is also enhanced by their body mass being concentrated close to their center of gravity (Feldhamer et al. (1), 2007). The hind limbs are unique within this class of mammals because they are able to rotate 180°, allowing the knees to point backward, which aids in flight maneuvering. They hang from the claws of their toes which is assisted by a special tendon locking mechanism, allowing them to cling to surfaces without expending energy (Feldhamer et al.(1), 2007).

Although nocturnal bat species' primary perception of the environment is through acoustic orientation with the use of echolocation and audible vocalizations, bats do have eyes and are not blind. When bats echolocate they emit high-frequency sound pulses from their mouth or nose and then discern information about objects in their path from the returning echoes. Hearing involves interpreting information about the environment from energy received as sound waves and provides the same information as vision in terms of size, shape, texture, distance, and movement (Feldhamer et al. (1), 2007). The information is able to be transmitted because the features of the object alters the original high-frequency sound pulse transmitted by the bat and are distinguished in the returning echoes (Feldhamer et al. (1), 2007). Most Microchiropterans have a tragus, which is a projection from the lower margin of the pinnae, or visible part of the ear, that is important in the receiving of echolocation pulses (Figure 2) (Feldhamer et al. (1), 2007). Facial ornamentation functions in the transmission of echolocation pulses because some species transmit ultrasonic pulses through their nostrils. Different bat species emit different frequency echolocation calls based on their environment and the particular action they are

undertaking, i.e. hunting, navigating, and mating. Sometimes, these differences are so unique to a species that, through the use of bat monitoring equipment, researchers are able to decipher a bat species type from the call. However, overlap in environment and behavior can make this technique unreliable for amateurs and experienced bat researchers alike.

Bats have evolved all the reproductive systems that have been described for mammals, which include delayed ovulation, delayed implantation, sperm storage and reproductive synchrony (Bradley, 2006). All of these reproductive strategies have evolved to ensure that the timing of birth provides them and their offspring with the greatest chance of survival (Bradley, 2006). Females generally have 1-3 offspring, depending on the environmental conditions such as food and roost availability. Having a low birth rate makes bats more susceptible to inhospitable environmental conditions, thus making them more at-risk for population decline than other species.

Bats' unique characteristics have made them a challenge to study which makes them decidedly worthy of further study as their importance to the environment and the value of the ecosystem services they provide to humans are not adequately assessed. Bat research should be made a priority as rapid development, which is characterized by a growing human population, removal of natural areas, and increased resource extraction, makes gathering data on bats natural habits increasingly unfeasible.

Bats of Illinois

Of the 1116 species of bats, there are 12 located in Illinois. Unlike the tropical species, temperate communities of bats are much less diverse. All species in Illinois are within the family Vespertilionidae (Feldhamer et al. (2), 2009). The bat species found in Illinois include the little brown bat (*Myotis lucifugus),* big brown bat *(Eptesicus fuscus),* northern long-eared myotis *(Myotis septentrionalis),* Indiana bat *(Myotis sodalis),* southeastern bat *(Myotis austroriparius),* eastern pipistrelle *(Pipistrellus subflavus),* gray bat *(Myotis grisescens),* eastern red bat *(Lasiurus borealis),* silver-haired bat *(Lasionycteris nostivagans),* rafinesque's big-eared bat *(Corynorhinus rafinesquii),* hoary bat *(Lasiurus cinerus),* and the evening bat *(Nycticeius humeralis).* The Rafinesque big-eared bat, southeastern bat, the Indiana bat and gray bat are endangered in Illinois while the later two are also federally endangered (Hofmann, 1996). Being within the same family denotes many similarities among Illinois bat species. For example, their body sizes

are all less than 30 grams (Feldhamer et al. (2), 2009). All Illinois bat species are insectivorous and many could be simply "classified as either moth or beetle strategists" (Black (1), 1974; University of Illinois, 2011). However, spatial and temporal differences in prey availability and particular roosting habits between species can create intraspecific variation for factors such as diet or relative activity in given areas (Feldhamer et al. (2), 2009). Illinois bat species' roosting habits hold influence over their diet as they modestly range from their roost when feeding.

Residency of Illinois Bats

There are year-round residents, potential year-round residents, and summer residents in Illinois (University of Illinois, 2011). The year-round residents include the big brown bat, little brown bat, northern long-eared myotis, Indiana bat, southeastern bat, and the eastern pipistrelle. The little brown bat is a colonial species with both sexes roost together in caves and mines through the winter. During the spring and summer, females form nursery colonies in hollow trees, under loose bark on trees, or in buildings while the males live alone or in small colonies roosting in trees, in rock crevices, or under siding or shingles of buildings. During the fall, both sexes roost in trees (University of Illinois, 2011). Both sexes of the big brown bat roosts in caves, tunnels, rock crevices, hollow trees, or buildings during the winter. During the spring and summer, females form nursery colonies in hollow trees or attics. Males are typically solitary during the early part of summer and roost in crevices in buildings or caves. Both sexes may be found together in roosts in late summer and fall (University of Illinois, 2011). The northern long-eared myotis and Indiana bat are colonial species where both sexes will roost in mines and caves in the winter. In the summer the females form small nursery colonies in hollow trees, under loose bark, or in minimally used buildings. Males continue to roost in caves during the spring and summer (University of Illinois, 2011). The southeastern bat is a colonial species that roosts mostly in caves but will also use of other natural and man-made features if caves are not available (University of Illinois, 2011). The eastern pipistrelle has both sexes roost singly or in small groups in caves and mines during the winter. In summer, females form moderately sized nursery colonies in caves, cliffs or under the eaves of buildings. Males are solitary throughout summer (University of Illinois, 2011).

Potential year-round residents include the gray bat, eastern red bat and silver-haired bat (University of Illinois, 2011). The potential lies in the lack of understanding of migration and

roosting habits of these bats. The gray bay is colonial and roosts in caves year round. The eastern red bat is solitary, taking shelter within crevices or hollow trees in the winter while they can be found hanging from the outer limbs of trees in the summer. They sometimes use shrubs or tall weeds as roosting spots in spring and fall (University of Illinois, 2011). Summer residents include the rafinesque's big-eared bat, hoary bat and evening bat (University of Illinois, 2011). The rafinesque's big-eared bat is colonial and roosts in caves, mines and buildings. The hoary bat is solitary and roosts in the tree's foliage while occasionally living in cavities. The evening bat is colonial and roosts in trees or occasionally in buildings (University of Illinois, 2011).

Habitat, Feeding Behavior and Migration of the Big Brown Bat (Eptesicus fuscus) and the Little Brown Bat (Myotis lucifugus)

The difference in roosting locations and times, along with a slew of other characteristics or conditions such as skull morphology, prey selection, population size, etc., define each Illinois bat species' role in their environment. *Eptesicus fuscus* and *Myotis lucifugus* are the species of focus in this study. In regards to population, these species are some of the most prevalent species in the eastern United States (Agosta, 2002; Saunders, 1988). Although these species both are within the Vespertilionidae family, their morphology and ecological preferences differ (Table 1) (Kurta and Matson, 1980; Whitaker and Gummer, 2000; Agosta et al., 2005; Brenner, 1972; Neubaum, 2005; Mills, 1975; Keen and Hitchcock, 1980; O'Farrell and Studier, 1974).

Table 1: Characteristics of *E. fuscus* and *M. lucifugus*

Characteristic	*Eptesicus Fuscus*	*Myotis lucifugus*
Mean Body Mass	19.50	7.92
Adult Sex Percentage	~65 males, 35 female	~73 males, 27 female
Sex Ratio at Birth	1:1	1:1
Diet Diversity Index	2.47	5.42
Hardness Index	4.59	2.32

E. fuscus, naturally using hollow trees for roosting and caves for hibernating, have become more closely associated with people than any other American bat through *E. fuscus* colonies' utilization of attics, church belfries, shutters, and loose boards and hibernating sites of houses, tunnels and storm sewers (Nowak, 1994). Therefore, *E. fuscus* or colonies of *E. fuscus*

have a relatively high possibility of being attracted to individual's property through the installation of bat houses or by providing larger building structures. However, the same qualities often make them target for expulsion or extermination (Whitaker (1), 1995).

As mentioned previously, *E. fuscus* is a year-round resident with generally unchanged summer and winter ranges; however, local movements to suitable hibernacula have been recorded, with the longest recorded movement being 180 miles and an average of 30-60 miles (Saunders, 1988). A population of *E. fuscus* simultaneously requires a maternity roost, summer day roosts, summer night roots and a number of hibernacula (Agosta, 2002). Although there is little information on *E. fuscus's* daily movement, the estimated home range is 43 mi (Saunders, 1988; Mills et al., 1975).

Emerging at dusk, *E. fuscus's* activity peaks 1-2 hours afterwards (Saunders, 1988). They prefer to forage above open habitats with scattered trees and in residential areas. It has been suggested that they return to used feeding areas (Nowak, 1995). Their general flight is steady and slow at about 10-11 mph and decreases to about 6-9 mph when foraging (Brigham, 1990; Saunders, 1988). They feed mostly on flying insects, in comparison to non-flying insects, including Diptera, Hemiptera, Homoptera, Lepidoptera, but feed most heavily on hard-bodied insects such Coleoptera. *E. fuscus is* often referred to as a "beetle strategist", especially in comparison to other comparable bat species (Feldhamer et al. (2); 2009, Whitaker (2), 1972; Black (2), 1972; etc). Whether *E. fuscus* should be termed an opportunistic eater is debatable. Some researchers attribute their active Coleopteran selection during low Coleopteran availability to discredit their role as opportunist (Brigham, 1990; Black, 1974; Whitaker 1995). Others view them as opportunistic due to their increased utilization of other insect species in the relative absence of Coleopterans (Anthony and Kunz, 1977; Brigham and Saunders, 1990; Griffith and Gates, 1985; Hamilton and Barclay, 1998). However, they are deemed generalists (Anthony and Kunz, 1977; Feldhamer et al., (2), 2009). The results of this research highlights *E. fuscus's* abundance of Coleoptera within its diet but since its feeding habits can change in response to a change in the present insect community, their role as a generalist will be incorporated into this research.

E. fuscus breeds in fall, although it can extend until March, and utilizes delayed fertilization. Generally, *E. fuscus* located west of the Rockies have a single offspring while those located east of the Rockies have twins (Nowak, 1994). The mean annual survival of adults is

relatively high, although it ranges from 10-77% in the first winter, with the maximum recorded lifespan of 19 years, with an average age of 2-3 years (Nowak, 1994).

M. lucifugus has separate roosts for day, night, hibernation and nursery purposes. Although a year-round resident, they generally migrate up to 171 miles (275 km) between their summer and winter roosts (Davis and Hitchcock, 1965). There is no researched data on the home range of *M. lucifugus,* however it is speculated that they travel a few miles between day roosts and feeding sites (Saunders, 1988).

Emerging at dusk, *M. lucifugus's* activity peaks 2.5 hours afterwards with a potential second peak before dawn (Saunders, 1988). They prefer to feed low over water at the margins of lake, streams, and ponds and along forest edges (Hough, 1957). Like *E. fuscus,* they also return to regularly used feeding areas (Anthony and Kunz, 1977). Flying at speeds of approximately 4-21 mph (6-34 km/hr), *M. lucifugus* generally feeds on small (3-10mm); flying insects although lactating females tend to consume larger prey (Saunders, 1988). *M. lucifugus* has the most diverse diet of any bat in the eastern United States and epitomizes the generalist characteristic commonly assigned to insectivorous bats. Their diets are notably influenced by local and seasonal insect abundance while there is no significant tendency toward specialization (Carter et al., 2003; Anthony and Kunz, 1977).

All of the above mentioned habits and characteristics of *E. fuscus* and *M. lucifugus* influence their role within the environment while impacting the ecosystem services they have the potential to provide. Differing feeding characteristics shape their ability to provide the ecosystem service of arthropod suppression. As natural arthropods suppressors, they hold potential to substantially reduce harmful arthropod pests, becoming beneficial if incorporated into agricultural systems.

Agricultural Methods and Management Strategies

Presently, the term sustainable has transcended specific definition due to the inability to evaluate truly sustainable practices in a world with a constantly increasing population and rapidly transformative technologies, communication, and abilities (USDA (2), 2011). However, the term can be applied to current agricultural practices in that it describes farming systems that are "capable of maintaining their productivity and usefulness to society indefinitely. Such systems... must be resource-conserving, socially supportive, commercially competitive, and

environmentally sound" (Ikerd, 1990). Sustainable agriculture involves an integrated system that works to satisfy human food and fiber needs while enhancing environmental quality and the natural resource base that the agricultural economy depends on through the efficient use of nonrenewable resources and the utilization of natural biological cycles and controls (UDSA, 2011). However, many agricultural operations choose not to employ these practices due to the increased knowledge, planning, and time that is required to implement such practices.

Many current agricultural practices utilize pesticides, i.e. herbicides, fungicides, and insecticides, with the belief that they most effectively and efficiently provide increases in production per unit input, also termed agricultural intensification (Food and Agriculture Organization of the United Nations (1), 2004). Considering reported dollar returns estimating from $3-5 for every $1 invested, those beliefs seem to be supported (Pimental (2), 1993). However, these practices artificially accelerate natural processes and fail to incorporate indirect costs into the dollar amount returned. Indirect costs are costs that are a result of an agricultural operation that is not reflected in the final market price. The indirect costs often take the form of harm to the environment. The continued use of pesticides, in conjunction with other less natural practices, i.e. monocultures, genetically modified organisms etc., has produced an unsustainable imbalance which holds the potential of harmful consequences for the integrity of agricultural land, the stability of the agricultural economy, and human health (Pimental (1), 2005; Pimental (2), 1993; Isenring, 2010; O'Shea and Johnston, 2009; Wickramasinghe, 2003).Therefore, although chemical methods appear to be the most cost-effective, the prolonged degradation to the environment, the soil and quality of the product has the potential to undercut the initial dollar return. For that reason, generating and implementing alternative agricultural methods will be of benefit to the economy and environment which will ultimately provide gain to individuals.

Agricultural Intensification and Pesticide Usage

Although the rate of land expansion has reduced dramatically in the last three decades, yields have continued to rise (Grigg, 1993). From 1700 to 1980, the total area of cultivated, or agricultural, land worldwide has increased 466% (Weber and Turner, 1992). Agriculture can be defined as the managing of terrestrial ecosystems which diverts their productive capacity to serve the needs of humans (Firbank et al., 2008). Agricultural intensification is defined as the increased production of agricultural commodities per unit input which may include land area,

labor, time, fertilizer, seed, and cash (Food and Agriculture Organization of the United Nations (1), 2004). This increase per unit commodity was attributed to a period of intense research and development of agricultural techniques and technologies from 1950-1990, deemed the "Green Revolution" (Food and Agriculture Organization of the United Nations (2), 2011). The Green Revolution was seen as necessary to spare the fate of starvation to millions of individuals in developing countries. A 1967 report of the U.S. President's Science Advisory Committee concluded that, "the scale, severity and duration of the world food problem is so great that a massive, long-range, innovative effort unprecedented in human history will be required to master it" (International Food and Policy Research Institute, 2003). Although the Green Revolution was able to defeat the initial bout of starvation, it has generated many issues regarding agricultural biodiversity, widespread use of agro-chemicals, the need for substantial irrigation, and discrimination of economically disadvantaged farmers (Food and Agriculture Organization of the United Nations (2), 2011).

In order to address the issues that were caused by the Green Revolution, another "innovative effort unprecedented in human history" will be needed (International Food and Policy Research Institute, 2003). The Green Revolution's focus on productivity is not enough to continue to sustain the world's growing population because it does not support sustainable food production. (Food and Agriculture Organization of the United Nations (2), 2011). Although the Green Revolution did modernize certain aspects of agriculture through its incorporation of heavy machinery certain aspects were simply intensified, such as the use of pesticides (Unsworth, 2010).

Pesticides Use in Agriculture

A pesticide is a substance or mixture of substances that are meant to prevent, destroy, repel, or mitigate any pest including insects, mice, weeds, fungi or microorganisms (EPA (2), 2011). The use of pesticides extends far into the past, with the first recorded use of insecticides dating 4500 years ago (Unsworth, 2010). The growth of synthetic pesticide predated the Green Revolution, becoming widespread in the 1940s with the discovery of dichlorodiphenyltrichloroethane, better known as DDT, benzenehexachloride, better known as BHC, aldrin, dieldrin, and captan (Unsworth, 2010). Although there had been reports of resistance to DDT and harm to non-target species, concern of consumers and policy makers was

low in regard to pesticides through the 1950s. However, Rachel Carson, through her 1962 book *Silent Spring,* surfaced the problems that could arise through indiscriminate use of these pesticides (Unsworth, 2010). This simply prompted scientists of the 1970s and 1980s to return to the lab to create a new regime of pesticides that did not carry the same associated risks as the former pesticides. Scientists of the 1990s then deciphered families of existing pesticides that have greater selectivity or better environmental and toxicological profiles (Unsworth, 2010). The newest pesticide chemistry has improved resistance management, improved selectivity, and refined use patterns (Unsworth, 2010). As of 2002, 327.4 million lbs. of pesticides were used nationally, with insecticides comprising 141.9 million lbs. or approximately 43% (Gianessi and Reigner, 2006). Illinois' total pesticide usage was 1.4 million lbs., with insecticides comprising 98% of that amount (Gianessi and Reigner, 2006).

Illinois Apple Orchard Practices and Concerns

Although all 50 states have farms or ranches with some apple production, the number of farms has continually fallen from nearly 34,000 in the late 1990s to 25,600 farms in 2007 (Slattery et al., 2011). The six states that dominate apple production are Washington (57%), New York (11%), Pennsylvania (4%), California (4%), Michigan (7%), and Virginia (3%) (USDA (3), 2005). Illinois constitutes less than 1% of apple orchards, containing ~50 throughout the state (Figure 3) (Orange Pippin Ltd., 2011).

The production of apples involves one of the highest rates of pesticide use, with insecticides being the most greatly used (Beaulieu et al., 2005; Slattery et al., 2011). As mentioned previously, insecticides have a range of negative effects although the full range is yet unknown. As this fact has gained publicity, there has been a fast-growing demand for organically grown apples, making apples one of the top three organic fruits purchased by consumers of organic foods (Slattery et al., 2011). A Washington State University (WSU) Study claims that organic and integrated apple production systems produce similar apple yields while maintaining higher soil quality and holding lower environmental impacts than conventional systems (Reganold et al., 2001). Since these findings have been published, the study is often cited in the battle against pesticides (Gianessi, 2006). However, apple production is exceedingly difficult due to the high rate of diseases and pests that face the industry including apple scab, fire blight, codling moth, oriental fruit moth, and many more, making organic and integrated production

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systems even more difficult to implement (Table 2) (Johnson, 1999; Gianessi, 2006; Mitchinson, 2011). The often highly endorsed WSU comparative apple production system study has been refuted by Gianessi (2006), with claims that the study "unjustifiably inflates the costs and risks of the conventional system while systematically favoring the organic system in its calculations and presentation of results. By correcting these biases, the opposite conclusion is supportable." Despite the conclusions of either study, the integration of bats into apple orchard systems, conventional or organic, holds the potential for bats to reduce total pest arthropods in a given apple orchard system.

Figure 3: Locations of Apple Orchards in Illinois

Table 2: Primary apple orchard pest insect's general information

Orchard Pest	Order	Life Cycle	Size	Most Widely Used Insecticides Against Orchard Pest
Codling Moth (*Cydia pomonella*)	Lepidoptera	2 generations (3 in warm years)	½ - ¾ inch	Guthion, Imidan, Diazinon, Lannate, Asana, Danitol
Oriental Fruit Moth (*Grapholitha molesta)*	Lepidoptera	3 generation (partial 4th)	¼ - ½ inch	Guthion, Imidan, Diazinon, Lannate, Sevin, Asana, Danitol, Intrepid, Avaunt
Plum Curculio (*Conotrachelus nenuphar)*	Coleoptera	1 generation	¼ inch	Guthion, Imidan, Diazinon, Asana, Avaunt, Assail, Calypso, Danitol, Ambush, Pounce
Obliquebanded Leafroller (*Choristoneura rosaceana)*	Lepidoptera	2 generations	¼ - 1 inch	Guthion, Imidan, Lannate, Asana, Confirm, Intrepid, Ambush, Danitol
Redbanded Leafroller (*Argyrotaenia velutinana)*	Lepidoptera	3 generations	¼ - $^2/_5$ inch	Guthion, Imidan, Lannate, Asana, Confirm, Intrepid, Ambush, Danitol
Apple Maggot (*Rhagoletis pomonella)*	Diptera	4 instars (generations)	$^1/_8$ -¼ inch	Guthion, Imidan, Diazinon, Lannate, Sevin, Asana, Danitol, SpinTor, Surround, Assail, Calypso

The Codling Moth (*Cydia pomonella*)

Originating in Asia Minor, *C. pomonella* is now found wherever apples are grown (Brunner (1), 1993). *C. pomonella* has been a staple pest of apple orchards in North America for over 200 years. It is one of the most destructive pest insects of not only apples but pears, quince, walnut, apricot, plum, peach and other *Prunus* species such as sweet cherry or almonds (Brunner (1), 1993; Alston et al., 2010; University of California, 2011; IPMNet, 1989). In general, there are two generations of *C. pomonella* a growing season with a third possible in an exceptionally warm season (Figure 4) (Johnson, 2004). A first-generation emergence occurs in mid-June with a second-generation emergence occurring in mid-August (Johnson, 2004).
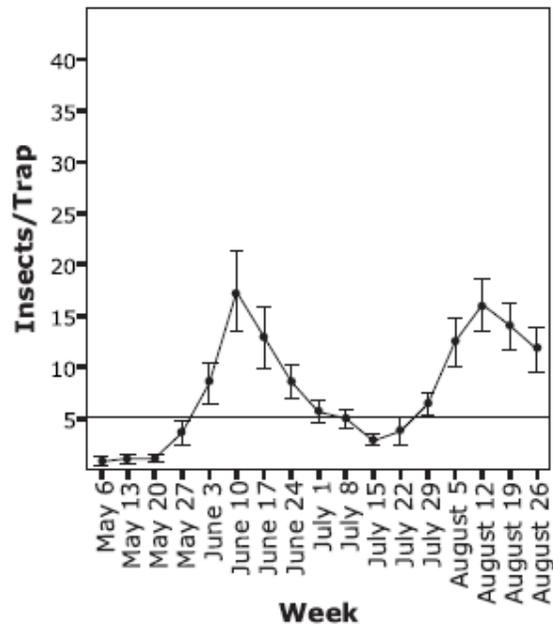
Figure 4: Average weekly capture to demonstrate life history of *C. pomonella*

Most management strategies are targeted at the larval stage of *C. pomonella*, especially the second-generation, as they are the most destructive stage; however, monitoring and management of the adult stages are advisable as a mated female moth lays 30-70 eggs (Figure 5) (Alston et al., 2010; Charlotte, 2011). The barely visible eggs are singly laid onto a leaf near fruit, hatching 6-20 days later depending on the temperature (Alston et al., 2010). Damage is caused by the newly hatched larvae tunneling into the fruit, feeding on the developing seeds and then tunneling out of the fruit leaving frass (excrement) around the exit hole (Figure 1). The larvae may then pupate and emerge as second or third generation adults in 10-20 days or enter diapauses and remain as larvae until the following spring (Alston et al., 2010). The overwintering larvae develop to the pupal stage when spring temperatures exceed 50°F (late February and early March) and undergo a 7-30 day development period to begin the cycle anew (Figure 5) (Alston et al., 2010).
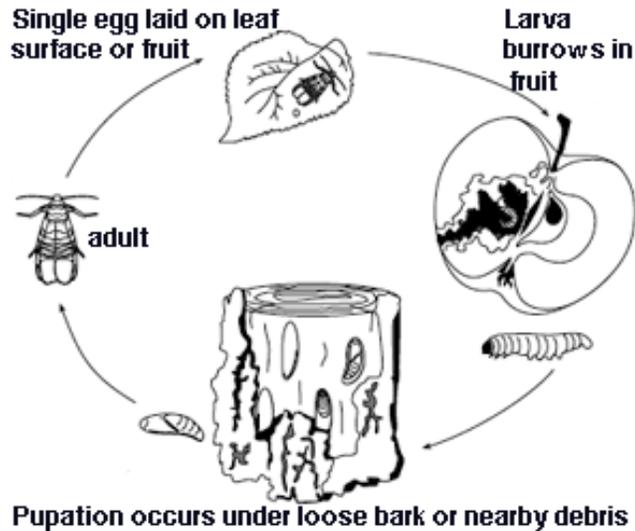
Figure 5: Life Cycle of *Cydia pomonella*

The most employed management method of *C. pomonella* is the use of insecticides, primarily the organophosphates azinphos-methyl (Guthion) and phosmet (Imidan) (Brunner (1), 1993; McCamant, 2007). Organophosphates are the most widely used group of insecticides in the world (Pesticide Action Network, 1996). Organophosphates are among the most acutely toxic pesticides to animals, deteriorating their nervous system (Pesticide Action Network, 1996). However, *C. pomonella* has shown increased resistance to many insecticides, which demands increased application and/or toxicity of the insecticide (IPMNet, 1989). As concerns increase over organophosphates effect on humans and ecosystems, various organizations and government agencies, including the EPA, are working to decrease or phase out their usage (Pesticide Action Network, 1996; Brunner et al. (2), 2003). In its place, other less toxic insecticides must be developed or other natural methods must be employed, resulting in an integrated pest management system.

Integrated Pest Management

For many farmers, wide-scale adoption of sustainable practices may not be tangible as such practices can require additional knowledge, resources and time to implement. However, the variety of sustainable agricultural practices makes the possibility of integrating one or many of them into conventional agriculture schemes more feasible. The mixture of sustainable and

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conventional methods is called "integrated" farming (Chivian and Bernstein (1), 2008). Integrated methods are highly beneficial because it allows agriculturists the ability to manipulate the ecosystem service they most desire and then alter their current operations to enhance that naturally occurring service. The idea of incorporating opposing methods to gain a more balanced and beneficial outcome can apply particularly to agricultural pest control methods.

Integrated pest management, or IPM, implies an integration of pest management methods with minimized economic and environmental risk. Due to the diversified methods incorporated, it can be assumed that chemical dependence is minimized because non-chemical methods had been investigated and designated as effective (Willson, 1992). The four methods that can be used when implementing IPM are biological control, mechanical/cultural control, chemical control and legal control (Willson, 1992). Biological control is classified into three approaches including a classical approach, an augmentation approach and a natural approach. The classical approach is implemented when dealing with a non-native pest by determining its native habitat, deciphering its naturally occurring predators and then, if feasible, importing, multiplying and then releasing/establishing the predator to the problem area. However, many precautions must be taken with this method as the release of another non-native organism has the potential for negative effects. Augmentation deals with native or non-native pests and involves the mass rearing and periodic release of natural enemies to supplement the natural enemy complex in a given environment. Natural biological control involves native pests and involves the utilization of natural predators through the selective use of cultural practices and considerate application of pesticides (Willson, 1992). Cultural and mechanical pest control involves the physical manipulation of the land or agricultural practices, such as crop rotation, hedge rows, and barriers. (Willson, 1992). Chemical control involves the use of pesticides and is the most readily recognized method of pest management (Willson, 1992). Legal pest control involves regulatory actions that prevent the immigration or dispersal of foreign or established pests (Willson, 1992). It is also necessary to understand the pests' life cycles, evaluate their interactions with the environment and be aware of current available pest control methods (EPA (1), 2011). That knowledge base can allow agriculturists to modify their current pest control practices to coincide with pests' natural variability which generally proves economically and environmentally beneficial (EPA (1), 2011).

Many of the above mentioned methods are interwoven and have aspects which contribute to the overall success of an IPM strategy. As environmental concern continually increases, desire to integrate more biological and cultural/mechanical methods is mounting (Willson, 1992). In many cases, cultural and mechanical methods support natural biological methods. Many times, maintaining agricultural land with pest control in mind often enhances natural predator activity. A prime example of such activity is the recruitment of bats onto agricultural land through altered land management practices and other alterations (Wickramasinghe et al., 2003; Fuller et al., 2005; Kunz et al., 2011). Since bats are a relatively elusive animal, altered practices aren't often aimed at bats incorporation which makes bats an often further overlooked natural biological control.

Potential of <u>*Eptesicus fuscus*</u> *and* <u>*Myotis lucifugus*</u> *as a natural pest control agent in an Integrated Pest Management Strategy*

As has been established, *E. fuscus* and *M. lucifugus* are insectivorous bat species that embrace the diet of a generalist. However, they do differ in the relative rates of prey selection, even if this is simply due to insect hardness (Fraser and Fenton, 2007; Freeman, 1981). Therefore, gauging the differences in their diet composition and feeding capacities will provide insight of the specific potential each species has as an arthropod suppressor.

The studies that have examined *E. fuscus'* diet have shown that they incorporate a variety of prey types, although they have a tendency to feed primarily on beetles and other hard-bodied insects, being flexible both temporally and spatially (Hamilton, 1998; Phillips, 1966; Whitaker (1), 1995; Whitaker (2), 1972; Whitaker (3), 1981). This means that their prey base includes agricultural pests. Research has shown that a single *E. fuscus* colony of 150 individuals can consume nearly 1.3 million pest insects in a night (Whitaker (1), 1995).

Although this type of research hasn't been approached in regard to *M. lucifugus* individuals or colonies, research has shown that on average a captive individual *M. lucifugus,* as well as *E. fuscus,* can consume 25% of their body mass in a night (Coutts et al., 1975; O'Farrell et al., 1971). It has also been estimated that an individual *M. lucifugus* at peak lactation needs to consume >100% of its own body mass, with a 7.9g bat consuming 9.9g of insects (Kurta et al., 1989). On average, a single adult *E. fuscus* weighs between 14-23 grams (Feldhamer et al. 2009; Best et al.; de Magalhaes and Costa, 2009) while a single adult *M. lucifugus* weighs between 7-

14 grams (Feldhamer et al. 2009; Harvey et al., 2011; Smithsonian National Museum of Natural History, 2011). A single *C. pomonella* weighs approximately 0.03 grams (Bloem et al., 1999). Despite these considerable reported numbers, this type of research is minimal but should be expanded in order to highlight bats' role as an agricultural asset which can then be incorporated into conservation considerations.

This research paper reconstitutes the data of relevant published papers to build on the idea that bats are economically and environmentally significant in the agricultural settings of apple orchards. More specifically, this research paper seeks to quantify *E. fuscus'* and *M. lucifugus'* reduction of the adult female *C. pomonella*, the corresponding reduction in *C. pomonella* eggs, and the ultimate prevention of *C. pomonella* larvae. Methods of land management that will support bat populations are discussed to facilitate incorporation of bats into apple orchard's IPM strategies. The future research goal is to quantify how reductions in *C. pomonella* and associated eggs can render a reduction in pesticide applications.

Methods

Quantifying and Analyzing <u>E. fuscus'</u> and <u>M. lucifugus'</u> Consumption of female <u>C. pomonella</u>
Published Data Incorporated into Analysis

This study was constructed through the use of previously published research, manuals, journals and articles that explain or discuss Illinois bat species' diet composition, Illinois apple orchards' pests, Illinois insect community dynamics, and Illinois apple orchards' pesticide usage (Anthony and Kunz, 1977; Black (2), 1972; Feldhamer et al. (2); 2009; Lee and McCracken, 2004; Whitaker (2), 1972, Minnesota Department of Agriculture, 2007; Gianessi and Reigner, 2006).

Studies that analyze Midwest bat species' diet composition are minimal, with studies specifically analyzing Illinois bat species' diet composition being even fewer. Therefore, the two species of bats, *E. fuscus* and *M. lucifugus,* were chosen based on the prevalence of published studies quantifying the composition of their diet through percent volume of insect order consumed (Feldhamer et al.(2), 2009; Carter et al., 2003; Lee and McCraken, 2004; Whitaker, 1995). Feldhamer et al., (2) 2009 researched prey consumption of eight species of insectivorous bats in Southern Illinois, making it the most applicable to this study due to its geographic

location. Other papers detailing the composition of bats diets were excluded due to inaccessibility or because geographic location of the study area was too distanced from Illinois (Cleveland et al., 2006; Lacki et al., 2007). From the most relevant papers, averaged percent volume of insects and spiders to order were generated (Figure 6 and 7). However, calculations which included numbers reported in papers that are not a part of the final analysis were included to quantify and visualize their influence on the final averaged percent volume of insects and spiders consumed (Figure 6 and 7).

The methods of the published research papers that were used in this study generally followed the methodology introduced by Kunz and Kurta (1988) and Whitaker (1988, 2004), or methods that were very similar. Kunz and Kurta (1988) described standard mist-netting techniques used in the capturing of the sample bats. Generally, researchers recorded the species, gender, age (juvenile or adult), body mass and reproductive condition for each individual. Whitakers (1988, 2004) methods carried out in the collection of fecal samples. Fecal pellets were collected and then stored in sealed vials until analyzed. Pellets were then placed in Petri dishes, covered in ethanol, teased apart and examined with a dissecting microscope at a magnification of 30x. Some studies also incorporated a modified version of Black's (1972) method to more accurately estimate percentage of Lepidoptera as they are often only represented by scales.

Methodology

Insect composition within bats species' diet was generated by averaging published quantities of the percentage volume of prey remains for insects and spiders (Fig. 6 and 7). For example, the reported percent volume consumption values of Coleoptera by *E. fuscus* were 72.2, 67.5, 73.7 and 57.9. By summing these values and dividing by the total number of values, 4, the averaged value of 67.825% volume of Coleoptera was determined. This method was repeated for each insect order that was present in the published data. The variability of insect composition within bat species diets was acknowledged by calculating the standard deviation of the differing published quantities of percentage volume of insects and spiders consumed by bat species (Table 1).

Obtaining the number of adult female *C. pomonella* consumed by *E. fuscus* and *M. lucifugus* was done by reproducing the methods presented in Cleveland et al., 2006. Calculating individual number of consumed *C. pomonella* required knowing the body mass ranges for *E.*

fuscus and *M. lucifugus*, the percent body mass *E. fuscus* and *M. lucifugus* can consume in insects, the average weight of *C. pomonella*, the sex ratio of *C. pomonella*, and the number of female *C. pomonella* that would naturally disperse into the crop (Table3; Table 4). Firstly, the number of *C. pomonella* that could be consumed by the bats if they were to only consume *C. pomonella* was calculated by taking the body mass of the bat, multiplying it by the percent body mass they could potentially eat and then dividing that number by the weight of *C. pomonella*. For example, 14 grams* 25% yielded 3.5 and then 3.5/0.03 yielded 116.66. That number (moths that have the potential to be eaten) was then multiplied by the percent Lepidoptera in the diet of the bat. For example, 116.66* 24.33% yielded 28.35. Then, using that number, divide by two to account for the sex ratio of *C. pomonella*. For example, 28.35/2 yielded 14.175. Then, use that number and multiply it by the number of female moths that disperse into the crops. For example, 14.17*15% yielded 2.12. That number can then be subtracted from the total number of female moths consumed. For example, 14.17-2.12 yielded 12.05. 12.05 is the total number of adult female *C. pomonella* consumed by a 14 gram *M. lucifugus* that is consuming 25% of its body mass in one night of feeding.

Table 3: Variables relating to *E. fuscus* and *M. lucifugus* needed to calculate number of *C. pomonella* consumed

Variable	*Eptesicus fuscus*	*Myotis lucifugus*
Range of Body Mass (grams)	14-23	7-14
Percent Body Mass Bats Consumed / Night	25-115	25-115
% Lepidoptera in Diet	1.76	24.3

Table 4: Variables relating to *C. pomonella* needed to calculate number of female *C. pomonella* consumed by *E. fuscus* and *M. lucifugus*

Variable	*Cydia pomonella*
Weight (grams)	0.03
Sex ratio	1:1
% Population that Naturally Disperses into Crop	15

Quantifying the number of larvae prevented due to <u>E. fuscus'</u> and <u>M. lucifugus'</u> consumption
of adult female <u>C. pomonella</u>

Published Data Incorporated into Analysis

In order to obtain the number of larvae that were ultimately prevented, the number of eggs prevented by *E. fuscus*'s and *M. lucifugus*'s consumption of adult female *C. pomonella* needed to be calculated, as eggs are the stage preceding the larval stage (Figure 5). That calculation required knowing the number of eggs laid by *C. pomonella*, the number of times *C. pomonella* can reproduce, and the percent reduction in survivorship that naturally occurs due to other predators. These variables were obtained from sources that studied the life cycle of *C. pomonella* and from studies that analyzed the predation of *C. pomonella* eggs (Alston et al., 2010; Glen, 1977; Glen and Brain, 1978).

Methodology

Obtaining the number of *C. pomonella* eggs prevented by *E. fuscus* and *M. lucifugus* was done following the guidelines presented in Cleveland et al., 2006. Therefore, I firstly found that *C. pomonella* lay 30-70 eggs each mating cycle and that they generally reproduce three times in their life cycle (Alston et al., 2010; Glen, 1977). I then used that information to presume that an adult female *C. pomonella* has the ability to lay between 90-260 eggs in her lifetime. However, this number is reduced due to natural predation. The study used in this paper found predation of *C. pomonella* eggs by earwigs to be 3-29% while it was 12-89% by Heteropterans and mites (Glen and Brian, 1978). It should be noted that these two are separated categories because Glen and Brian's (1978) methods assumed that earwigs take all their eggs before other predators are able to act and thus alter the number of eggs available to Heteroptera and mites. However, using these numbers a new range of eggs that survive natural predation was able to be produced. In order to find the low number of eggs that survived earwig predation, the low range number of eggs laid by *C. pomonella* was multiplied by the low range of eggs that were made prey by earwigs: 90 * 0.03 = 2.7. This number, which was the number of eggs preyed on by earwigs, was subtracted by the total number of laid eggs: 90 - 2.7 = 87.3. This number became the new number of eggs to continue calculations with. To find the final number of eggs that survived all natural predation, 87.3 was multiplied by the low range of predation by Heteropterans and mites: 87.3*0.12 = 10.476. This number was subtracted from the number of eggs which survived

earwig predation: 87.3 - 10.476 = 76.824. Therefore, 76.824 eggs would be prevented by *E. fuscus's* and *M. lucifugus's* consumption of one adult female *C. pomonella.* These calculations assume that if fewer eggs are laid then less predation occurs, hence the pairing of 90 laid eggs to the rate of 3% predation by earwigs. Similar calculations were completed for the high range of laid eggs (260) and high rates of predation by earwigs (29%) and Heteropterans and mites (86%), resulting in 25.76 eggs surviving all forms of natural predation, producing a range of 25.76 – 76.824 *C. pomonella* egg survivorship.
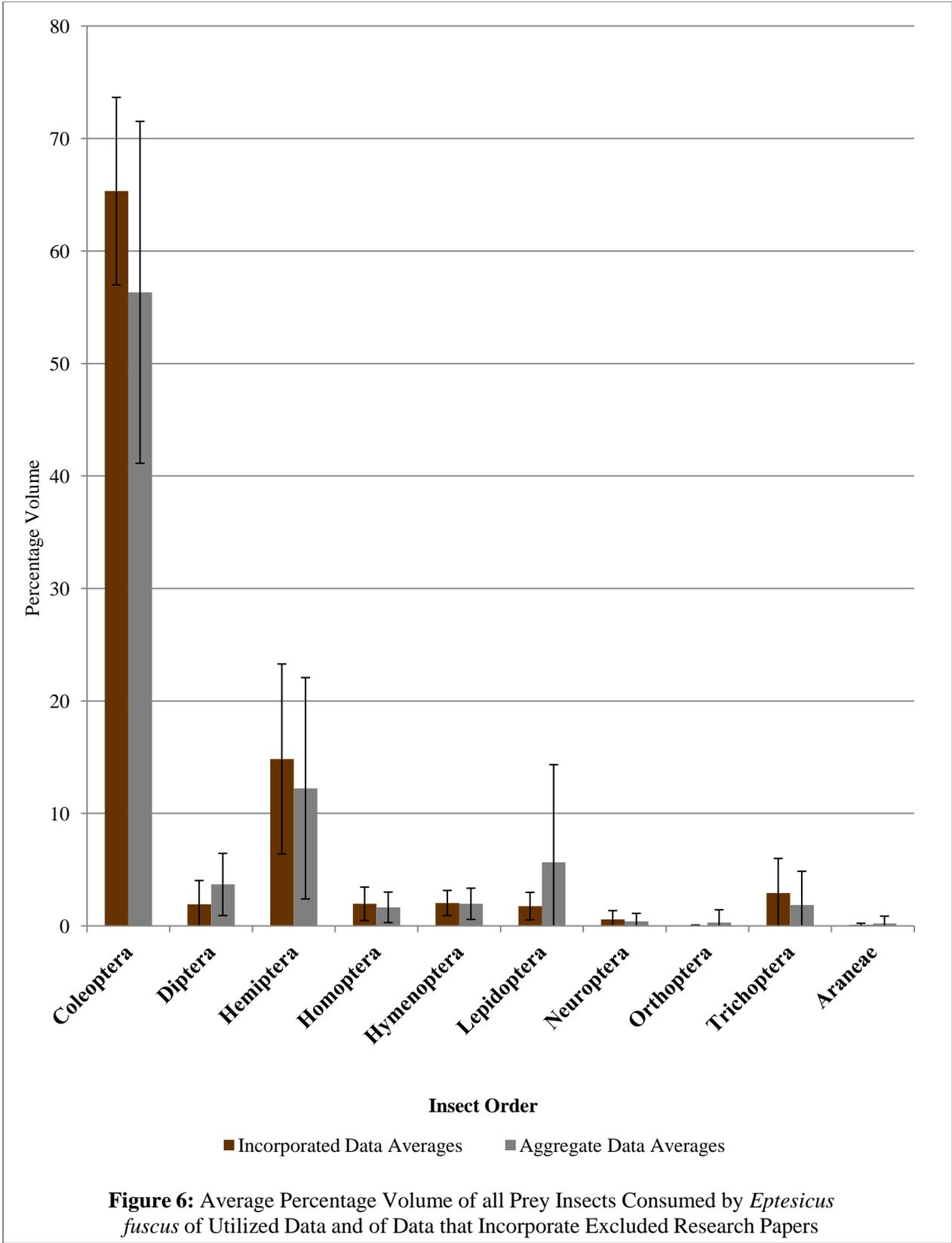
It was assumed that all eggs which would have survived natural predation would continue their life cycle to become larvae. In order to find the number of larvae prevented by bat's consumption of one adult female *C. pomonella,* predation statistics of *C. pomonella* larvae were found. In a study by Solomon et al. (1976), *C. pomonella's* larvae were preyed upon by birds at rates of 94.9% and 95.6%, generating a survivorship rate of 4.75%. The number of larvae which survived through the egg stage, 76.824, was multiplied by the survivorship rate of 4.75% to obtain the number of larvae that survive predation: 76.824* 0.0475 = 3.649. A similar calculation was done using the survived egg number of 25.76, which resulted in 1.2236 larvae which would have survived natural predation, producing a range of 1.2236 - 3.649 *C. pomonella* larval survivorship.

The high and low range of larvae prevented by *E. fuscus's* and *M. lucifugus's* consumption of adult female *C. pomonella* was then calculated. This calculation required combining the range of larvae that survived natural predation with *E. fuscus's* and *M. lucifugus's* range of consumption of adult female *C. pomonella* which includes the bat's body mass and bat's percent body mass consumed/night. The largest range of larvae prevented was generated by coupling low larval survivorship with low *C. pomonella* consumption and high larval survivorship with high *C. pomonella* consumption. For example, using the *E. fuscus's* upper body mass, the highest moth consumption was multiplied with the highest rate of larval survivorship, giving the upper most range of prevented larvae: 21* 3.649= 76.629. However, final numbers were rounded so 76.629 became 76. This process was then repeated for each bat species, but only coupling high percent body mass consumed by bat/night with high survivorship of larvae and low percent body mass consumed by bat/night with low survivorship of larvae because those calculations produced the largest potential range of larval prevention.

Results

The results in this study were created through the compilation of published data that examined the diet composition of *E. fuscus* and *M. lucifugus*. The results show all insect orders that are included in the diet composition of *E. fuscus* and *M. lucifugus* (Figure 6, 7). They also show the potential consumption of *C. pomonella* by *E. fuscus* and *M. lucifugus* based on the range of body mass in the adult bat and the range of percent body mass a bat would consume in a night.

Figure 6 and 7 display the percent volume of insect order averages from publications that were included in this study as well as the averages for all publications that reported the percent volume of insect order in the diet composition of *E. fuscus* and *M. lucifugus*. Table 5 and 6 show the standard deviations for the percent volume of insect order averages from publications that were included in this study as well as for all publications that reported the percent volume of insect order in the diet composition of *E. fuscus* and *M. lucifugus*. Every percent volume of insect order consumed between *E. fuscus* and *M. lucifugus* are different. Specifically, the percent volume of Lepidoptera in *E. fuscus's* diet is 1.76 while it is 24.33 for *M. lucifugus.*
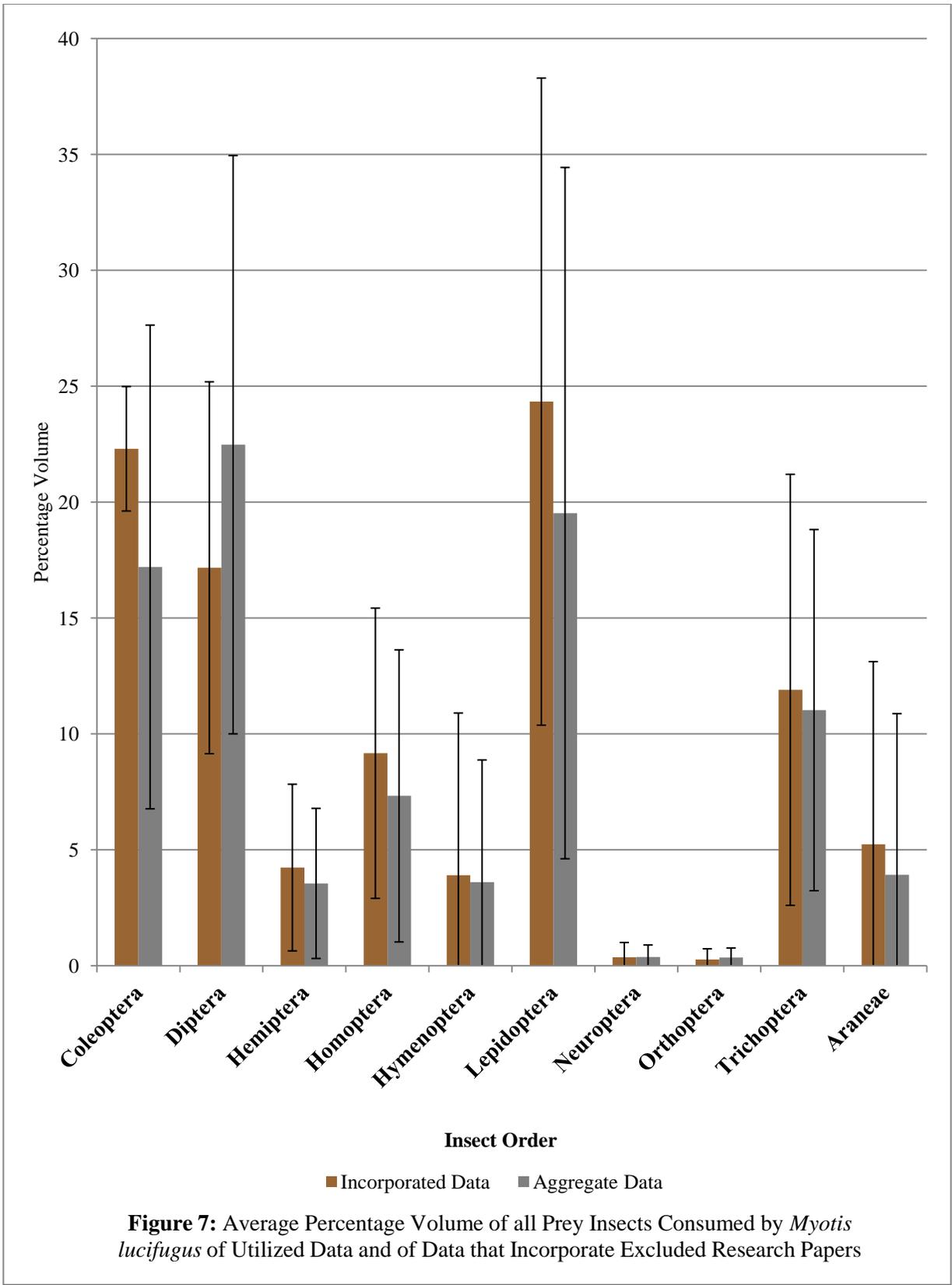
Figure 6: Average Percentage Volume of all Prey Insects Consumed by *Eptesicus fuscus* of Utilized Data and of Data that Incorporate Excluded Research Papers

Figure 7: Average Percentage Volume of all Prey Insects Consumed by *Myotis lucifugus* of Utilized Data and of Data that Incorporate Excluded Research Papers

Figure 6 and Figure 7 display *E. fuscus's* and *M. lucifugus's* overall diet composition. Figure 6 shows that Coleoptera composes approximately 65% volume of *E. fuscus's* diet when looking at the set of data that is incorporated into the final results of this study. The percent volume drops to approximately 56% when considering all data that was found on *E. fuscus's* diet (Figure 6). Each of the rest of the insect orders (Diptera, Hemiptera, Homoptera, Hymenoptera, Lepidoptera, Neuroptera, Orthoptera, Trichoptera, Aranea) compose less than 15% volume of *E. fuscus's* diet (Figure 6). Figure 7 diplays a very different diet composition of *M. lucifugus.* Lepidoptera comprimises that highest percent volume of *M. lucifugus,* although it is closely followed by Coleoptera and Diptera when looking at the set of data that is incorporated into the final results of this study (Figure 7). The percent volume of Coleoptera and Diptera seem to switch when looking at the bars representing all data collected (Figure7). Overall, *M. lucifugus's* diet composition is relatively evenly spread out across most all insect orders (Figure 7).

Table 7: Comparison of potential consumption of adult female *C. pomonella* at low consumption (25% body mass) by *E. fuscus* and *M. lucifugus*

	Eptesicus fuscus	*Myotis lucifugus*
Low Body Mass	3	6
High Body Mass	5	12

Table 8: Comparison of potential consumption of adult female *C. pomonella* at peak consumption (115% body mass) by *E. fuscus* and *M. lucifugus*

	Eptesicus fuscus	*Myotis lucifugus*
Low Body Mass	13	28
High Body Mass	21	55

M. lucifugus holds a greater capacity as a suppressant of *C. pomonella* than *E. fuscus.* On average, a 14 gram *E. fuscus* has the ability to consume between 3-13 adult female *C. pomonella* while a 24 gram *E. fuscus* has the ability to consume between 5-21 adult female *C. pomonella*, when considering the range of percent body mass consumed per night (Table 7, Table 8). The average mean body mass of *E. fuscus* is 19.50 grams (Feldhamer et al., 2009). On average, a 7 gram *M. lucifugus* has the ability to consume between 6-28 adult female *C. pomonella* while a 14 gram *M. lucifugus* has the ability to consume between 12-55 adult female *C. pomonella,* with both ranges being based on the range of percent body mass that can be consumed on a given

night (Table 7, Table 8). The average mean body mass of *M. lucifugus* is 7.92 grams (Feldhamer et al., 2009). Regardless of the differences in consumption, each species holds some potential as a suppressant of *C. pomonella.*

Table 9: Comparison of potential larvae prevented due to *E. fuscus*'s
and *M. lucifugus*'s low consumption (25% body mass) of adult female *C. pomonella*
in combination with low larval survivorship

	Eptesicus fuscus	*Myotis lucifugus*
Low Body Mass	4	7
High Body Mass	6	15

Table 10: Comparison of potential larvae prevented due to *E. fuscus*'s
and *M. lucifugus*'s peak consumption (115% body mass) of adult female *C. pomonella*
in combination with high larval survivorship

	Eptesicus fuscus	*Myotis lucifugus*
Low Body Mass	47	102
High Body Mass	76	201

Following the pattern in both bat species' ability to consume adult female *C. pomonella*, *M. lucifugus* has greater potential to prevent larvae then *E. fusus* (Table 9 and Table 10). On average, a 14 gram *E. fuscus* could prevent 4-47 larvae while a 24 gram *E. fuscus* could prevent 6-76 larvae, when considering the range of percent body mass consumed per night (Table 9, Table 10). On average, a 7 gram *M. lucifugus* could prevent 7-102 larvae while a 14 gram *M. lucifugus* could prvent 15-201 larvae, when considering the range of percent body mass consumed per night (Table 9, Table 10).

Discussion

This study examined the potential role *E. fuscus* and *M. lucifugus* held as natural suppressants of adult female *C. pomonella* as well as the number of larvae that would be prevented as a result of adult female *C. pomonella* consumption. This study found that *M. lucifugus* has greater potential as a suppressant of adult female *C. pomonella* than *E. fuscus.* Later research would determine potential pesticide reduction due to the decrease in *C. pomonella* larvae. Although ability as a suppressant of *C. pomonella* between *E. fuscus* and *M. lucifugus*

varies, each species is potentially beneficial if incorporated as one aspect of an integrated pest management strategy.

E. fuscus's and *M. lucifugus*'s consumption of *C. pomonella* is possible since central characteristics of the bats coincide with characteristics of *C. pomonella. E. fuscus*'s and *M. lucifugus*'s most active feeding period is ~1-3 hours after dusk which corresponds with *C. pomonella*'s emergence and most active period which falls during the hours surrounding sunset (Gharekhani, 2009). *C. pomonella*'s two population peaks coincide with both bat specie's population peaks which fall in mid-June and mid-August. As mention previously, the second generation of *C. pomonella* is the most harmful as it occurs more closely to the time of harvest (McCamant, 2007). The active feeding periods of both bat species extend through the period of *C. pomonella's* population peaks, with E. *fuscus* actively feeding April through October, or 210 days of the year, and *M. lucifugus* actively feeding from mid-May to early September, or 106 days of the year (Whitaker (1), 1995; Fenton and Barclay, 1980). Since *E. fuscus's* and *M. lucifugus's* feeding habits align with *C. pomonella's* active periods, both bat species are capable suppressors of *C. pomonella.*

Most of the differences in quantity of *C. pomonella* consumed by *E. fuscus* and *M. lucifugus* can be attributed to their natural characteristics (Table 1, Table 3). Consumption differences often reflect differences in bats body mass and percent body mass a bat can consume per night, both of which influence the types of insects consumed (Table 1, Figure 6, Figure 7). For example, Feldhamer et al. (2009) found a significant relationship between mean body mass of bats of southern Illinois and prey hardness. As *E. fuscus* is one of the heaviest bats in Illinois, such data supports *E. fuscus's* tendency to consume hard bodied insects, such as beetles (Figure 6). The relatively low feeding diversity index of *E. fuscus* can be partially attributed to its high prey hardness index (Feldhamer et al., 2009). *M. lucifugus* lacks the high prey hardness index that makes *E. fuscus* inclined to consume particularly beetles, which attributes a high feeding diversity index to *M. lucifugus* (Table 1, Figure 7) (Feldhamer et al., 2009). These differences affect the abilities of *E. fuscus* and *M. lucifugus* to suppress specific types of insects. Although those differences do have the most substantial effect on the amount of *C. pomonella* consumed in a night by either species, other characteristics, such as surrounding environment, adjacent insect community, differing times of bat's development, prey detection, etc., also influence their capacity to consume *C. pomonella*.

Although *E. fuscus* can weigh nearly three times the amount of *M. lucifugus, E. fuscus's* consumption of adult female *C. pomonella* is considerably lower than *M. lucifugus* for reasons mentioned in the above paragraph. This study determined that *E. fuscus* can consume between 3-21adult female *C. pomonella* per night while *M. lucifugus* can consume between 6-55 adult female *C. pomonella* per night (Table 7, Table 8). These quantities were used to determine the amount of potentially prevented *C. pomonella* larvae. The number of *C. pomonella* larvae that would be potentially prevented reflected the number of adult female *C. pomonella* moths consumed per night by the two bat species. This study found that by the bat's nightly consumption of adult female *C. pomonella, E. fuscus* had the potential to prevent 4-76 larvae while *M. lucifugus* had the potential to prevent 7-201 larvae (Table 9, Table 10). These numbers demonstrate that *E. fuscus* and *M. lucifugus* have great potential to be integral within an apple orchard's IPM strategy.

Incorporation of <u>E. fuscus</u> and <u>M. lucifugus</u> into an Apple Orchard's IPM Strategy

Besides characteristics that influence *E. fuscus's* and *M. lucifugus's* consumption of *C. pomonella,* there are other characteristics that make the recruitment of *E. fuscus* and *M. lucifugus* into an IPM strategy to apple orchards in Illinois valuable. For example, both *E. fuscus and M. lucifugus* travel only a few miles from their roost to forage which means that once they have established themselves, they will likely continue to forage within the proximity of that area, serving as a dependable pest suppressant (Saunders, 1988). Similarly, both *E. fuscus* and *M. lucifugus* have been found to return to feeding sites that they have found successful (Agosta, 2002; Buchler, 1976; Belwood and Fenton 1976; Anthony and Kunz, 1977; Whitaker et al., (7) 1977; Whitaker et al., (3) 1981). These characteristics make both bat species a reliable natural suppressant of *C. pomonella.*

The incorporation of *E. fuscus* and *M. lucifugus* into an IPM results in costs and benefits. The execution of a new pest management strategy inherently involves some risk. The costs are most associated with initial investment and the possibility of an unsuccessful IPM trial. Incorporating *E. fuscus* and *M. lucifugus* into an IPM strategy requires farmer's investment in some type bat houses or bat structures. Farmers may also choose to provide bats with foraging passageways through the inclusion of hedge rows or other habitat corridors which may result in a loss of farmland. Even if integration of *E. fuscus* and *M. lucifugus* is successful, farmers may be

unsatisfied with the pest control the bat species provide when comparing it to the instantaneous results achieved through pesticide use.

Despite the drawbacks, the successful incorporation of *E. fuscus* and *M. lucifugus* allows farmers to gain long-term advantages often overlooked in strictly conventional apple orchards and natural pest suppression. Striving to maintain long term resilience and health of agricultural land that is heavily inundated with agricultural chemicals has been greatly ignored because the same agricultural chemicals have provided supplementary nutrients, keeping agricultural land simply viable. The incorporation of IPM, by nature reducing chemical dependence to some degree, fosters naturally occurring processes among the many organisms within an apple orchard. Also, the health risks faced by humans and other organisms are lessened. This is exceptionally beneficial for bats with many studies showing that pesticides negatively affect bats whether it's through direct mortality, altered behavior, transference of toxins to nursing young or a reduction in prey base (Agosta, 2002; Fuentes-Montemayor, 2011; Eidel et al., 2007; O'Shea and Johnson, 2011). Most all of the above mentioned benefits are more enduring than the instantaneous benefits received from insecticides.

It is often difficult to make agricultural pest management decisions based on future projected benefits. However, by working to understand the relationships among the components of an apple orchard, farmers should realize the benefits that can be amassed by exchanging their chemically-reliant practices with an IPM strategy as IPM strategies long-term benefits associated with them.

Quantifying Economic Gain from the Reduction of <u>C. pomonella</u> by <u>E. fuscus</u> and <u>M. lucifugus</u>

Economic gain would be established using an avoided-cost approach which places a value on pest control services by assessing the costs that society avoids as a result of that service being available and an input of production (Cleveland et al., 2006). Avoided-costs are discussed in relation to the ability to reduce pesticide use based on the incorporation of bats into an IPM strategy (Cleveland et al., 2006).

Future Data Collection for Improved Model Estimates

In the future, this study will work to more thoroughly analyze the ecological variance between the *E. fuscus* and *M. lucifugus.* Results in this study were constructed based on the percent volume of insect to the order in *E. fuscus's* and *M. lucifugus's* diet. Although some papers did report specific species, they were not incorporated as they did not reflect apple orchard pest insects. In order to gain a more accurate amount of the consumption of *C. pomonella,* fecal samples from *E. fuscus* and *M. lucifugus* could be collected from selected apple orchard sites within Illinois. Fecal analysis would be completed following Whitaker (1988, 2004) or using quantitative polymerase chain reaction, a more precise molecular method. Insect surveys would also be completed on the selected apple orchard sites.

Recording of the type of environment that both surrounded and composed the apple orchard would be beneficial when considering habitat correlations with rates of bat activity and foraging. Similarly, collecting data on the insect community that the bats foraged in would allow more accurate deductions and precise conclusions about their diet composition. Light traps would be used in order to construct the nighttime insect community.

Obtaining pesticide application records from farmers from the selected apple orchard sites would provide understanding in the variation of pesticide regimens used against *C. pomonella.* Also, comparisons between differences in insect communities could be potentially be inferred from differences in pesticide regimens. Obtaining data on the above mentioned variables would allow this study to become more specific in its scope.

Conclusion

Reducing dependency on pesticides in apple orchards requires the incorporation of integrated pest management. Perpetuating naturally occurring pest predation in apple orchards is an environmentally sound form of integrated pest management because it does not introduce non-native species or chemical substances. Both *E. fuscus* and *M. lucifugus* have potential to be beneficial within the integrated pest management strategies of Illinois apple orchards, with *M. lucifugus* demonstrating a superior nightly consumption of *C. pomonella* over *E. fuscus.* Future analysis will provide data on the number of larvae that are prevented as well as the potential reductions in pesticide applications as a result of *E. fuscus's* and *M. lucifugus's* consumption of

C. pomonella. Conducting field studies of *E. fuscus's* and *M. lucifugus's* consumption of *C. pomonella* as well as insect communities within Illinois apple orchards will increase the accuracy of these results. Results concluded from the field data would provide a more thorough understanding of *E. fuscus's* and *M. lucifugus's* consumption of *C. pomonella* within Illinois apple orchards.

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