Periodical Cicada: Effects on Predation and Resource Cycling in Terrestrial and Aquatic Environments

Derek James Valenti
Stillwater, New Jersey

Bachelor of Arts in Environmental Sciences, University of Virginia, 2012

A Thesis presented to the Graduate Faculty of the University of Virginia Candidacy for the Degree of Master of Arts

Department of Environmental Sciences

University of Virginia
August 2014

Abstract

In America, the *Magicicada* species has a unique life cycle unlike that of most insects. Cicadas in America have a life cycle that lasts either 13 or 17 years. A majority of their lives is spent underground living off of root xylem. During the 13^{th} or 17^{th} year of their life, cicadas emerge from the ground and form what are known as "chorus centers" to mate. Upon emergence, the cicadas crawl to the surface with nutrients that were attained deeper in the soils. In this paper, it is examined how the pulsed resource of a cicada emergence can cause changes in different environments and animal behavior.

The emergence of cicadas in mass numbers provides a unique opportunity for observation in the environment from predation to plant growth in both aquatic and terrestrial environments. Certain predators, such as opportunistic foragers, are most likely to capitalize on the resource availability. Avian predators are found to employ different consumption techniques throughout the span of emergence. One of the cicadas best defenses it employs is predator satiation, in which the insects emerge in mass quantities which allows for predation to consume a small percentage of the population. Cicadas that are not consumed by predators will go on to reproduce and eventually die and can cover an entire forest floor. The decaying carcasses are high in nitrogen and result in heightened growth for shallow rooted plants. A similar process is seen in aquatic environments except that decomposition happens at a faster rate, and the effects of a cicada outbreak can be observed in a shorter frame. A pulsed resource such as the *Magicicada* provides a unique opportunity to promote environmental changes, which can also offer insight

into how environments and animals may react to drastic changes resource abundance.

Table of Contents

List of Figures

List of Tables

Acknowledgments

Thank you to my thesis committee: Professor Macko, Professor Shugart and Dean Laushway for their never ending patience and support for me throughout this process

Thank you mom and dad for always being there for me. Without you I would not be where I am today.

1. *Introduction:*

13 and 17 Year Cycle

Around the world, there are over 2,000 of known insect species of the family Cicadoidea. The species can be found on every continent except Antarctica and is capable of living in different climactic conditions, from deserts to Arctic environments. One of the most identifiable differences between cicada species is the length of their life cycle, which can range from one to 17 years. Their larger nutrient filled body and lack of major defenses make the insect an appealing option for predators and a delicacy to humans in some countries. This paper examines the life cycle of *Magicicada* and how cicada emergences affect environmental and animal responses.

The American cicada, genus *Magicicada,* presents one of the most unique life cycles of any insect in the world. Figure 1 shows the *Magicicada* lineage can be traced back to one species as early as 3 million years ago. Today there are 7 different species that emerge from the ground once every 13 or 17 years. There are 3 major species that emerge every 13 years, each beginning with the prefix tre-; *M. tredecim, M. tredecula and M. trecassini.* The 17 year cicada each begin with a prefix of sept- and consisting of *M. septdecim, M. tredecula and M. tredecassini*. The 7 species are often refered to as –decim, -decula, and –cassini because there is plasticity in years of emergence but there are 3 genetic differences in the types of the *Magicicada.* Interbreeding between species is possible, but it is rare. The 17-year cicada emergence is found in the north while the 13-year cicada is found more in the southern North America. One theory argues the split in the 13- and 17- cicada emergence period arose from climactic differences dating back 3 million years ago (Grant 2005).

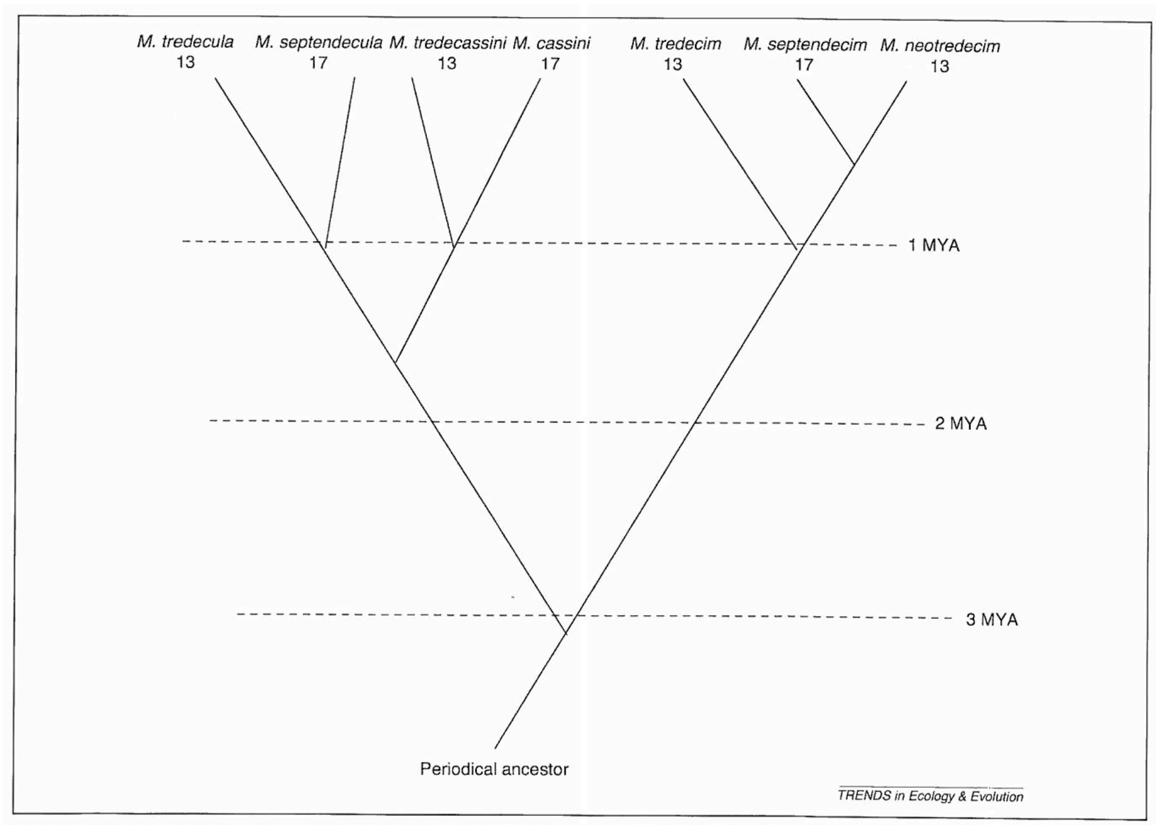

Figure 1: History of the *Magicicada* lineage based on mitochondrial DNA. Source: Grant, (2005).

There are many theories as to how these insects developed such a unique life cycle. With the long-period emergence of the cicada, there are only small windows of opportunity to gather information on the periodic appearance of the cicada. There are two main ideas as to why the cicadas life cycle is so unique:

1) The first theory developed is predator satiation by having such a long life cycle, every time the cicada rise from the ground, their above-ground predators will initially be hesitant to consume the insect. Once predators find that the cicada is an edible prey, the above-ground population is so dense that predators will consume only a small percentage of the total insect numbers (Grant 2005). The size of the cicada emergence is so large that it would not be plausible for the life cycle to be shorter than the 13 or 17-year cycle. If their cycles were shorter then the insects would not be able to sustain such a high population on a shorter emergence time.
2) The second theory, research has shown that the split of the *Magicicada* species dates back to 3 million years ago, but the major changes in the species came around 1 Mya. During the period of glacial cycles, it is believed that the beginning of the long life cycle of the *Magicicada* arose due to the harsh climatic weather patterns. With global cooling, there were limited opportunities for the cicada population to thrive, therefore the selective emergence of the cicada evolved in order to seize the optimal opportunity for reproduction while the species had lower populations (Grant 2005). The 13- and 17- year emergence may have developed because temperatures became warm enough to provide the cicadas with a small window of opportunity to emerge and reproduce. With this theory the question arises of why predators were not able to entirely consume the low population of cicadas.

Both theories presented bring up valid arguments as to why the cicadas emergence is as unique as it is; a favored theory is that the emergence developed from a combination of these two theories.

The evolution of the 13- and 17-year life cycle of *Magicicada* is thought to have arisen from a species of cicada with a shorter life cycle. Due to this shorter life cycle it is found that the *Magicicada* have developed some plasticity to their life cycle (Marshall *et al.* 2000). In areas where the 17 and the 13-year cicada populations overlap, it was found that the 17-year cicada could sometimes emerge during a 13-year cicada outbreak and vise versa. Figure 2 shows the plasticity of the emergence years. The most common change in a species emergence is the 17-year cicada emerging 4 years earlier with the 13-year cicada.

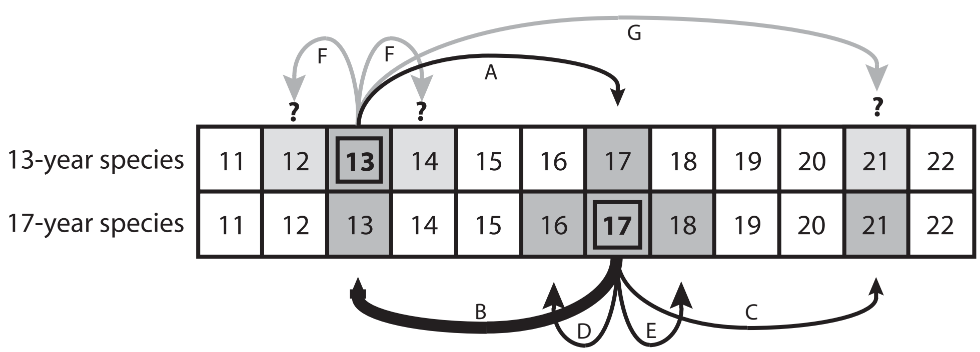

Figure 2: Chart displaying the plasticity of 13- and 17- year life cycle. Source: Marshall *et al.*, (2011).

Life Cycles

The cicada does not have the longest life of any insect on the planet, falling behind the Splendour Beetle and Termite Queen, but it does possess the longest period in the juvenile development stage. While in juvenile stages, the cicada acquires all its nutrients by feeding on plant roots. During the juvenile life span, the cicada is similar to an aphid (Christensen *et al.* 2010). During the underground life span, the cicada goes through five nymphal instars. *Instar* is defined by Robinson *et al*. (2007) as "insect developmental periods between successive exoskeleton moltings. " The fifth and final stage of the nymphal development can last as long as 5 years.

As a nymph, the cicada is commonly found from 7 to 38 cm deep in the soil. The depth of the insect is strongly dependent on the presence of surrounding roots; in certain areas the nymph has been found as low as 60 cm in the soil (Williams and Simon 1995). Fifth stage *instar* nymphs are typically found at shallower depths than earlier stages of the nymph.

While underground, the nymphs will attach themselves to the roots of the surrounding plants and drink the xylem fluid of the roots for its entire juvenile life span. It is not unusual for a cicada to remain attached to a single root for the entire 13 or 17-years that the nymph is underground. There are two advantages of drinking xylem fluid as opposed the tapping into the phloem. First, they avoid many of the plant defenses and an accumulation of excess sugars. Second, cicadas can use the excess water from xylem to help mold their underground cells. Xylem fluid is a dilute nutrient source that has small concentrations of amino acids and minerals (Williams and Simon 1995). It has been suggested that this slow acquisition of nutrients and amino acids plays a part in their long life cycle.

Upon the 13 or 17-year of the underground period where cicadas grow to full size, there is an unknown mechanism that which communicates to the juvenile cicada that it is time to emerge (Christensen 2010). Cicada emergence tends to occur in late spring to early summer. Densities of emergence can range from 10 – 370 m^{-2} (Wheeler *et al.* 1992). The insects will breach the top of the soil from dusk until dawn and typically crawl up the nearest plant or standing structure. Once above ground, the cicada will begin to shed its exoskeleton at dawn the following day.

Mating

On a typical emergence, the male cicadas are the first insects to rise from the ground. During their ascent from the ground, cicadas will molt into the adult form within 24 hours of emerging. Upon emergence the males will form what is known as a “chorus circle. ” Cicadas are large insects, over 2 cm in length, and are not able to travel far distances. They will typically emerge in close broods. A brood is a group of cicadas that emerge in the same year and are isolated from other groups (Williams 1995). The males congregate together and will omit a unique mating song in order to attract female companions.

Within a few days after the male cicada emergence, female cicadas will begin to ascend. Similar to the male cicada, the female cicada will not travel far from their emergence areas. The female cicada will migrate towards the male cicada chorus centers. When moving to these chorus centers, the females respond to the overall sound of the male chorus centers, but they will not respond to any specific male until they are close enough to begin to identify differences between male chorus calls.

Once at a chorus center, female cicadas will begin to single out male mating partners. A female will identify her appropriate mate by acknowledging a few different characteristics. Each individual male will demonstrate two different calling techniques. The first portion of the call is known as the "main-element," which consists of the group chorus constant pitch that identifies the chorus centers. The second part is the "Frequency downslur. " This downslur is what separates one male from another. The downslur is a unique beat that will be identifiable to different females when they get close enough to chorus centers to begin finding differences in each male. These downslurs are most prominent in the –decim species (Marshall 2000). Marshall (2000) suggests that the most effective males that found partners demonstrated some sort of movement while singing to their prospective mates. So the most successful male cicadas are the insects that are able to produce a powerful "main-element," distinct "frequency downslur," combined with identifiable movement that draws interest from surrounding females.

When a female cicada arrives at the male chorus center she will begin to select a male based on the before-mentioned characteristics. Once a female decides on a suitable male, she will draw the male's attention by doing what is known as a wing flick. The wing flick which she performs is done at the downslur of her chosen male mate. By performing this wing flick at the downslur of the chosen mate then she will be able to identify her specific mate from a group of males.

When the male is identified as a viable mate, then the male cicada will continue to sing to the female as he walks up next to the female. If the female continues to respond to the male's downslur then the female is signaling to the male that she has chosen him as a mate. A male cicada will continue the song until he mounts his partner. Once the male cicada has mounted the female, she can still reject the male by continually performing the wing flick. If this happens, then the female has indicated that she has chosen another mate other than the male that is with her.

With the dense population of male cicadas in the chorus center, it would seem logical that there is a high level of competition between males at the center. However, there is not an unusual amount of competition observed between males. With the dense number of males in the chorus centers, there are a large number of females that emerge following the male emergence as well. If a male cicada chooses to try and outcompete a partner, he would have to take flight from his branch or chorus area and soar to the female of choice. In order to take flight, the male cicada will have to stop his song on order to reach his target. By the time he gets close enough to the female, there is a chance the female has already chosen her mate and will not display interest in the male. Since the female population emerges in such a large abundance, the most effective way for a male cicada to find a counterpart is by continuously chorusing, downslurring and moving to make himself noticeable for a mate. Any time he spends being silent is lost time to find a mate.

On rare occasions, a male cicada will find competition with another male over a female. The male that was originally chosen by the female will begin to compete with the new male. The chosen cicadas will compete with the other cicadas by attempting to mimic the other cicadas chorus calls and downslurs (Marshall 2000). By mimicking the opposing male, the first male will create a downslur that occurs exactly where the other males downslur is and this will reduce the likelihood of the female cicada to show interest in the new male. This continuous mimicking of the opposition will ensure the female keeps her attention on her initial male and will deter the newly arrived male away.

This mating technique is found in all *Magicicada*, but is more prominent in certain species over others; *M. cassinni* was the species found competing with each other. Certain species are species-specific with their wing flick. Such species as *M. cassinni* will only mate with males of the exact same species while other species such as *M. septendecim* can be heterospecific with mates (Marshall 2000). Part of this occurrence is due to the overlap of certain species. Even though the wing flick is species-specific, the flick is similar enough for different species to get it confused with females of the same species.

Oviposition

Once a female has mated, she will no longer be able to mate with another cicada. The male will insert a copulatory plug that inhibits the female from mating again. After the female has fertilized her eggs, she will then choose a young twig or branch on a near by tree. With the most popular tree found to be a white ash, but most cicadas will pick any tree as long as the branch or twig is an appropriate diameter (Speer *et al.* 2010). The female cicada deposits her eggs by creating a slit in the twig that is 10-20 centimeters in length. In this slit she can lay anywhere from one to several dozen eggs. In a female cicadas lifetime she can lay up to several hundred eggs. The adult female cicadas life typically lasts about 5-6 weeks above ground where they will typically die of disease, infection or get eaten. The emergence of the cicada nymph will not happen until after the adult cicada population is deceased. Once the nymphs emerge they will fall to the ground and dig until they find a suitable root to feast on and the life cycle will start over again.

Ovipositon into twigs can result in a pruning or flagging of that twig. A flagging branch is one that is hanging or broken that has dead leaves. These small slits in large trees have minimal effects, but younger trees will have more pronounced scarring. Young trees are composed of thinner branches, and they offer more opportunities for oviposition (Ahern *et al.* 2005). Due to this, smaller trees will have a harder time recovering from a cicada emergence than larger ones. Aside from oviposition, the pulse resource of the *Magicicada* offers a unique opportunity for the surrounding environment in which the cicada occupies during its period of emergence.

2. *Environmental Impacts*

The majority of the life of a cicada is spent underground; because of this their diet consists primarily of xylem fluids from plant roots. Most cicada nymph broods live in close proximity to one another underground until they grow to their full size. Their emergence, which can be over a million per hectare, provides a unique situation for the environment. The pulse emergences of the cicada species allow the cicada to summit in massive numbers, at points yielding over a million insects in one acre. An appearance of insects in this quantity provides a resource pulse for the environment that it is not able to experience except on rare occasions. The cicada emergence has such a vast effect that there are noticeable changes from the types of plants that are typically able to thrive in certain environments to changes in the eating habits of different mammals because of the mass insect outbreak.

Mammal behaviors

Cicadas provide unique opportunities for animals that are in the surrounding environments of a cicada emergence. Most mammals are accustomed to scavenging for food, due to a lack of food in an environment. When the resource pulse of cicadas emerges and is the dominant source of nutrition in the environment, animals that consume insects as a main diet have an abundance of food and nutrition for a period of time. Because of this abundance of food, it is found that certain animals would capitalize on the cicada abundance and demonstrate predatorial characteristics. Certain bird and rodents demonstrated uncharacteristic behaviors in response to the resource pulse, such unusual behaviors include venturing from the predators typical hunting grounds in order to prey on the mass cicada population (Krohne *et al.* 1991).

With little defenses, large size, and possibly hundreds per m^{-2} cicadas offer a rare opportunity for predators near an emergence area. With the insect covering the forest floor to the canopy, it is expected to see rodents and birds preying on the cicada populations (Storm *et al.* 2007). Of the ground rodents, some species capitalized on the cicada abundance while others chose to avoid preying on the insect.

Such species as the fox squirrel (*Sciurus niger*) and eastern chipmunk (*Microtus pinetorum*) completely avoided cicadas as a source of nutrition during the emergence, and opossum (*Didelphis virginiana*), white-footed mouse (*Peromyscus leucopus*) and eastern mole (*Scalopus aquaticus*) were scarcely found consuming the insects (Mumford and Whitaker 1982). It is unusual that the eastern mole did not consume many cicadas because their diet strongly consists of invertebrates. It is believed that the cicada is not a common diet of the mole due to its majority of life underground. The mole was not even found to have cicada nymphs in its stomach either as well (Storm *et al.* 2007).

Table 1: Food habits of different mammals during a period of *Magicicada* emergence. Source: Storm and Whitaker, (2007).

Prey Type	*Blarina brevicauda*	*Didelphis virginiana*	*Microtus ochrogaster*	*Microtus pinetorum*	*Peromyscus leucopus*	*Procyon lotor*	*Scalopus aquaticus*	*Sciurus niger*	*Tamias striatus*
Sample Size	10.0	1.0	4.0	2.0	3.0	6.0	6.0	2.0	4.0
Animalia	100.0	40.0	0.0	0.0	25.0	80.9	98.3	0.0	11.6
Bird	0.0	15.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Earthworm	41.0	0.0	0.0	0.0	0.0	15.0	70.5	0.0	0.0
Mollusk	0.0	0.0	0.0	0.0	0.0	6.7	16.7	0.0	0.0
Anthropoda	59.0	25.0	0.0	0.0	25.0	59.2	11.1	0.0	11.6
Arachnida	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0	0.0
Crayfish	0.0	10.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Insecta	59.0	15.0	0.0	0.0	25.0	58.4	11.1	0.0	11.6
Unidentified	0.0	0.0	0.0	0.0	0.0	0.0	0.8	0.0	0.0
Carabidae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.5
Coleoptera	2.0	0.0	0.0	0.0	0.0	0.0	5.0	0.0	0.0
Diptera	4.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Formicidae	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.0
Insect larvae	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3
Lepidoptera	0.0	0.0	0.0	0.0	0.0	6.7	5.0	0.0	0.0
Magicicada	53.0	15.0	0.0	0.0	25.0	51.7	1.7	0.0	3.8
Plantae	0.0	60.0	100.0	100.0	75.0	19.2	0.0	100.0	88.8
Blackberry	0.0	0.0	0.0	0.0	26.7	0.0	0.0	0.0	0.0
Fruit	0.0	0.0	0.0	0.0	25.0	0.0	0.0	0.0	0.0
Mast	0.0	0.0	0.0	0.0	0.0	0.0	0.0	25.0	65.0
Mulberry	0.0	60.0	0.0	0.0	0.0	16.7	0.0	75.0	23.8
Seeds	0.0	0.0	0.0	0.0	23.3	0.0	0.0	0.0	0.0
Vegetation	0.0	0.0	100.0	100.0	0.0	2.5	1.7	0.0	0.0

(Table 1, Storm *et al.*) Animals that were found to have the highest percentages of cicadas in their stomach, such as raccoons, are considered opportunistic foragers. Raccoons will capitalize on the most abundant and easiest prey for food. During the emergence of a cicada brood that is in the area of a raccoon's territory, raccoons will utilize the availability of the pulse resource. Since raccoons are such opportunistic foragers, research done by Storm *et al.* (2007) revealed that raccoons have one of the highest percentages, over 50 percent, of cicadas remnants found in their stomach of all the animals.

Both the white-footed mouse and the short-tailed shrew were found to have cicada remnants in their stomachs during an emergence (Krohne *et al.* 1991). Although both species demonstrated habits of eating cicadas, they displayed different responses in population abundance in the year of the cicada outbreak. The white-footed mouse is an omnivore that typically has an abundance of food available. In spring and summer months when cicadas are not present the mouse is able to acquire sufficient food by eating plants and berries (Krohne *et al.* 1991). Since the white-footed mouse is able to sustain a healthy diet in years without pulse resources, there is no significant change in population following the cicada emergence.

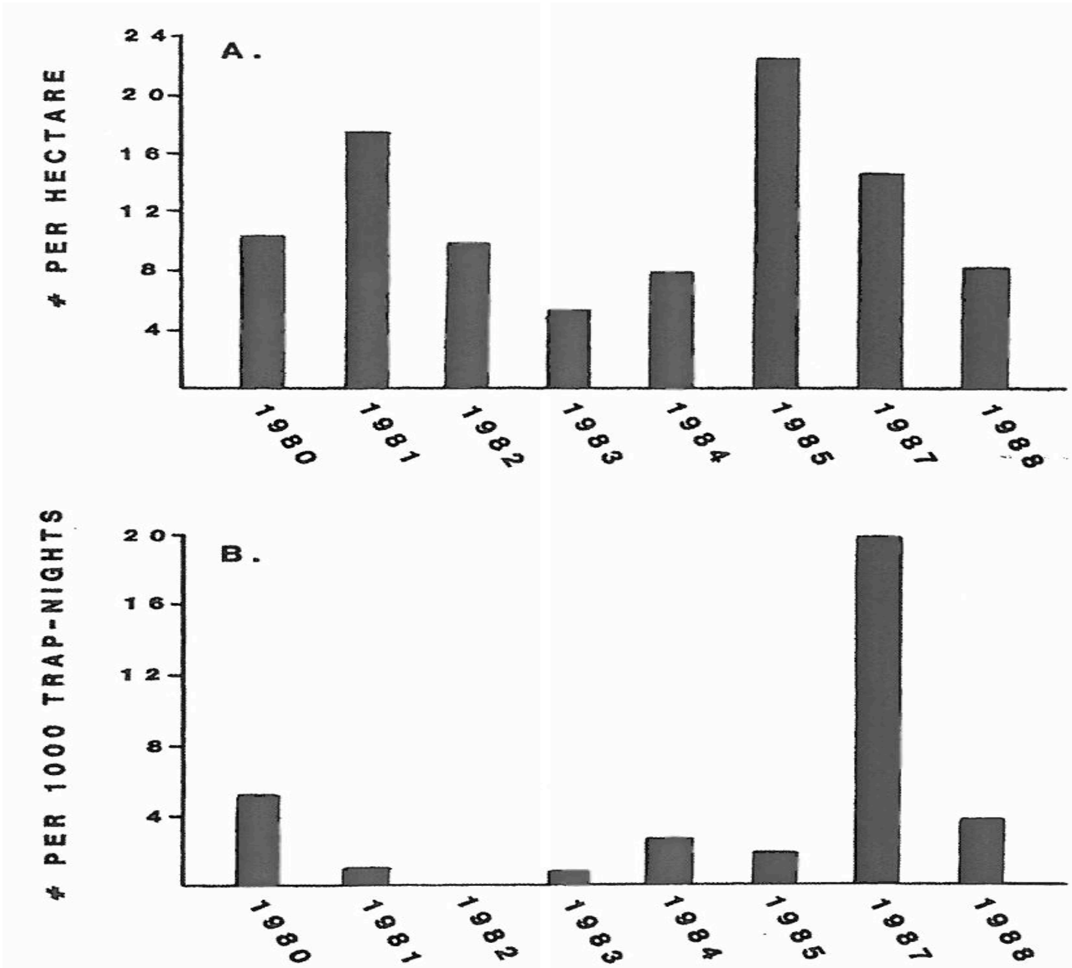

Figure 3: Comparison of summer peak densities of *Peromyscus leucopus*, white-tailed mouse (A) and *Blarina brevicada*, short-tailed shrew (B). Source: Krohne *et al.*, (1991).

In the research done by Krohne *et al.* (1991), a drastic change in the short-tailed shrew (*Blarina brevicauda*) population in the year of the cicada emergence was observed. In the year of the cicada, the short –tailed shrew population was more than 4 times the average calculated density of the total shrew population. . There are a few theories for such a large change in shrew abundance in Krohne *et al.* research area, which is composed of a deciduous forest. A possible explanation for this increase in shrew abundance may be due to three non-mutually exclusive factors: increased reproduction, better survival of offspring, or shrew immigration. Krohne *et al.* (1991) believed that the cicada emergence did not result in an extended period of reproduction for the shrew so the larger abundances are more likely due to a higher survival of offspring and shrew immigration. This research suggests that with a higher concentration of insects in the study area allow for a greater opportunity for adult and juvenile shrews to attain proper nutrition for better survival. Shrews are most commonly found in grasslands. The scope of this study was performed in a deciduous forest. This type of environment is not a typical shrew habitat, because of the over abundance of cicadas that emerged in the forest, the shrew displayed an uncharacteristic action of leaving its normal habitat of grassland for an opportunity for an abundance of food in the forest. Other animals, such as the red winged blackbird, have also displayed this immigration characteristic during a cicada outbreak as well.

The male cicada chorus centers are sometimes so loud that they will often deter predators from approaching the center (Simmons *et al*. 1971). The red-winged blackbird (*Agelaius phoeniceus*) is a species that is commonly found on a forest edge. In rare occasions the black bird will venture into the forest to find prey. During the emergence of Brood XIX, at large emergence of the 13-year cicada in the southeast, it was observed that the red-winged black bird strayed from the bird's ordinary predatorial techniques and ventured into the forest to begin preying on the nutritional cicadas.

The peak predation time for the birds to prey on cicadas was found during the peak cicada emergence in June. In the initial time of the study, the bird consumed the entire cicada in under a minute (Steward *et al.* 1988). Over a three-week period, the amount of time taken to fully consume a cicada nearly doubled. Initial findings showed that the black bird was impartial to the sex of the cicada it was consuming and would eat the exoskeleton along with the innards of the insect.

After some time had passed, it was observed that the black birds were able to discriminate between male and female cicadas and the birds would only consume the female cicadas, the male cicada bodies were filled with air used for calling to attract a mate while the females were filled with nutrients in preparation for egg deposition. Over time not only were the black birds able to select only female prey, but their consumption time also increased. This increase occurred for two reasons; instead of consuming the entire body of the cicada, the blackbird would slit open the cicada's abdomen and only consume the innards of the insects leaving the exoskeleton. The second explanation for the lengthier time of consumption is a result of the black birds becoming full of the pulse resource (Steward *et al.* 1988). With the abundance of food, blackbirds and other animals are able to become selective foragers with their food.

The cicadas do not possess many different defense tactics to prevent themselves from becoming prey. Two of their most successful traits they have for survival is a loud chorus center and predator satiation where the entire species emerges can emerge in the millions. Within a chorus center, individual cicadas can display some small defense tactics that will deter a predator away. These tactics were found to have the highest success rates later in an emergence when most predators had filled their stomachs and could afford to be more selective in their predation. These defense characteristics were found almost exclusively in males, which may have assisted the blackbird in identifying a male from female cicada. The only time a female cicada was observed to be defensive is when she was attempting to deposit her eggs in a young twig. If a predator were threatening to come close, the female would immediately take flight (Steward *et al.* 1998). Male cicadas were observed to demonstrate eight different reactions when approached by a threat. Those reactions were: walk away, fall, fall/fly, fly, fly/squawk, fall/squawk, squawk/stand still, and stay inactive (Alexander 1962). Of these different defense tactics, the least effective maneuver displayed was to remain inactive giving the predator an easy target for consumption. Every insect that stayed motionless in front of prey was captured, while over 95% of the insects that displayed the fly and squawk technique were able to escape their prey (Table 2). Those who escaped their predators were able to survive and pass on their genes to the next generation of cicadas. Throughout the emergence period red-winged blackbirds became so selective that they would select the cicadas, which demonstrated the fewest defense tactics.

Table 2: Successful and unsuccessful attack percentages of red-winged blackbirds based on cicada behavior. Source: Steward, Smith and Stephen, (1988).

Predator attack (%)	Cicada behavior exhibited			
	Inactive ($N=55$)	Fly ($N=111$)	Fly-Fall ($N=53$)	Fly-Squawk ($N=22$)
Successful	100	44.1	56.6	4.6
Unsuccessful	0	55.9	43.4	95.4

Impact on Plants and Nutrient Cycling

As mentioned earlier, the belowground life of a cicada provides a unique opportunity for a cycling of the below ground nutrients to the soil surface. Cicadas spend nearly their entire lives feeding on the xylem of tree roots. While underground the cicada goes through 5 *Instar* stages of growth (White 1975). The fifth stage of development can last as long as 5 years. In the fifth stage the cicada will reach its final nymph stage before it emerges from the ground and molts into an adult cicada.

In the fifth *instar* stage, the cicada will reach full growth and will have attained nearly all of its nutrition from the root xylem and the soil around it. With the cicada living its life, on average, prior to emergence about 10 to 40 cm below the surface, the nutrients that the cicada brings to the surface are typically not available to shallow rooted plants.

In a test area that was performed in an orchard and non-orchard environment, it was found that the average adult cicadas body yielded the following concentrations elements in (mg/kg): As (62), Cu (0. 015), Pb (0. 4), and Zn (166). The exoskeleton of the cicada revealed to have smaller concentrations of cooper, iron, aluminum, lead, and arsenic as well (Robinson 2007). The concentration of the Al in emerging cicadas is higher than other underground invertebrate in the same soil. There are two plausible explanations for these higher aluminum concentrations found in cicadas: passive assimilation, where the insoluble clay minerals the cicada is living in underground adhere to the exoskeleton of the nymph, or the Al is taken from root xylem and transferred to the exoskeleton. Seen in Table 3, once a nymph sheds its exoskeleton the adult cicada is composed of lower concentrations of aluminum. The element composition of the cicada element anatomy is one that reflects the environment that it is surrounded by. The body of the adult cicada is strongly composed of the nutrients found in root xylem, while the exoskeleton is made up of the components of the soil the insect is living in.

Table 3: Chemistry of adult cicada bodies and pre-molt nymph relative to maximum tolerable dietary limits for small animals. Source: Robinson *et al.* (2007)

	Site	Mn	Fe	Cu	Zn	Al	As	Pb	Hg
		mg/kg dry weight							
Adult cicada (mean)	Orchard	193	210	59	167	<100	2	0.4	0.01
Nymph (estimated mean)	Orchard	218	642	56	168	260	3	4.2	0.02
MTDL† (NRC, 1980)		400	500	200	500	200	50	30	2.00

† Maximum Tolerable Dietary Level, minimum of poultry–rabbit levels.
The estimate of mean cicada nymph chemistry is based on a mass-weighted average of nymphal exoskeleton and adult body means.

In environments where a cicada brood emerges in mass numbers such as 370 insects per m^{-2}, the cicada can have a large effect on the nutrient cycling of an environment. On a large-scale view of an ecosystem, cicada broods will not influence an entire forest, but a small scale area can prosper from the pulse resource (Wheeler 1992). Compared to typical litter fall, cicadas present an opportunity to have a significant increase of nitrogen, phosphorus and potassium in an environment.

Table 4: A comparison of cicada nutrients and relative importance in litter fall. Source: Wheeler *et al.*, (1992).

Variable	Litter fall ($g\ m^{-2}$)	Cicada ($mg\ m^{-2}$)	Relative importance (%)
Iron	4.3	0.42	0.01
Magnesium	3.0	2.9	0.1
Calcium	38.0	4.6	0.01
Sodium	0.4	2.0	0.5
Potassium	2.8	13.9	0.5
Phosphorus	1.0	8.3	0.9
Nitrogen	14.8	121.0	0.8

In a more concentrated, denser population of cicadas, a forest floor can be covered in cicada carcasses. These carcasses will have direct and indirect effects on the surrounding environment. Elements and minerals that are abundant beneath the forest floor will, for a period of time, be available for plants on the surface of the forest floor. In Table 4, the cicada density was found to be a small 6. 7 m^{-2} while densities have been recorded as high as 370 m^{-2}. Even with the smaller density the carcasses provide an opportunity for a nitrogen increase on the forest floor. Since nitrogen is known to be one of the main limiting factors in plant growth, the addition of nitrogen to the forest floors help encourage plant growth. In sample plots, there was a 306% increase of ammonium and 249% increase of nitrate on the forest floor. A direct result of these deaths on the forest floor is an abundance of bacteria and fungi within 2 to 3 weeks of the carcasses landing on the forest floor (Yang 2004). With this nitrogen increase, results showed that smaller plants such as the bellflower produced seeds that were 9% larger than control groups.

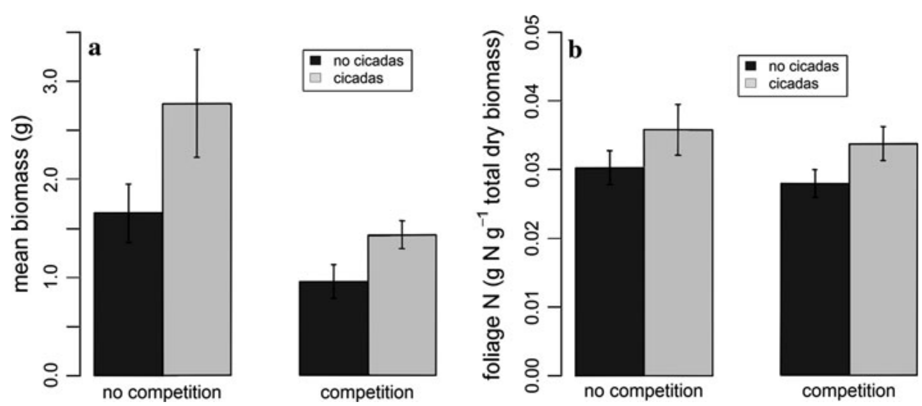

Figure 4: Bar Graphs of Bellflower biomass. Comparing intraspecific competition with neighbors and fertilization with cicadas. Source: Yang, (2012).

At the chorus centers where numbers can be in the thousands or even millions, cicadas will consume small amounts of leaves and the females will deposit their eggs in young branches and twigs that can result in the death of the twig. With mass numbers, it seems logical that there would be a noticeable decrease in plant growth and wood accumulation over the following year of a pulsed cicada emergence, but research has shown otherwise. In the years following a cicada emergence, there is an increase in the amount of wood accumulation and primary productivity in forested areas (Wheeler 1992). The result of this increase of wood accumulation is due to the increase of ground fertilization by the cicada brood. The increase of nitrogen and fertilization of the soils to the surface provides an opportunity quicker growth of plants than the forest has seen in prior years of an emergence even though female cicadas use branches for oviposition.

Effects in aquatic environments

As mentioned earlier, cicada population typically will not travel far from their emergence areas. They will form their dense chorus centers in trees or shrubs in forests or fields. Due to this, nearly the entire species that is not prey will fall to the soils below their chorus centers and affect the soils in those areas. On occasion, these cicada populations are located near an aquatic environment, and the pulse resource falls into the aquatic instead of terrestrial environment. Each year aquatic environments typically experience a pulse resource in the fall with the deposition of leaf litter into streams and lakes. The summer input of cicada carcasses offers a rare summer pulse resource opportunity that offers a high nitrogen concentration than what is seen on leaf litter (Menninger *et al.* 2008)

In aquatic systems there are similarities to terrestrial environments, but also some large differences. Similar to terrestrial ecosystems, bacteria are the first to react to the cicada detritus. These pelagic bacteria result in an increase of phosphate and ammonium in the water sources. As a result of these increases in the aquatic system there was also a significant increase in primary productivity in the environment.

Although there are some similarities in the two environments, aquatic environments display faster reactions then found in terrestrial systems. In studies performed by Nowlin *et al.* (2007), it took three to four days to decompose cicada carcasses in a pond environment compared to two to three weeks in a terrestrial environment. Maximum levels of phosphate and ammonium were also reached at this time. After 30 days, phosphate and ammonium levels had returned to original concentrations that they were prior to the appearance of the cicada (Nowlin 2007). During this period of increased concentrations of nutrients, there was also an increase in primary productivity, and a large increase in herbivorous and carnivorous zooplankton within two weeks of the appearance of the carcasses in the environment.

After two months of the detritus in the aquatic there was a significant increase in snail populations in the environment. The herbivorous snails were able to thrive with the large increase in the primary productivity (Nowlin 2007).

In a different study by Menninger *et al.* (2008), examined cicada retention and respiration in two different stream environments. Using a disturbed land, composed of an area that had undergone construction with a modified riparian zone and newly planted young trees, and a control group of a natural growing environment. The retention study showed that cicadas were carried an average of

13 meters downstream of where they entered the stream. The body of the insect is fairly buoyant and would often get trapped in shallow sediment patches, leaf packs, root wads and debris dams. In the areas where cicada emergences were near a stream, Menninger *et al.* (2008) found a significant change in stream respiration.

In order to test for change in respiration, it was tested prior to cicada emergence and 3 times during the emergence period (Days 12, 26, 40). Around the intact stream environment there was a significantly larger density of emerging cicadas, with a difference of over 20 cicada holes per m^{-2}. The disturbed site is believed to show a smaller emergence due to riparian forest modifications, construction may have destroyed appropriate nymph habitat. At both sites, it was found that there was a significant detritus input in both streams from days 13-35 of the emergence period. As seen in Figure 5, the maximum input days occurred from day 21 through 26. Throughout this time period it was recorded that there was little variation in leaf litter entering the stream.

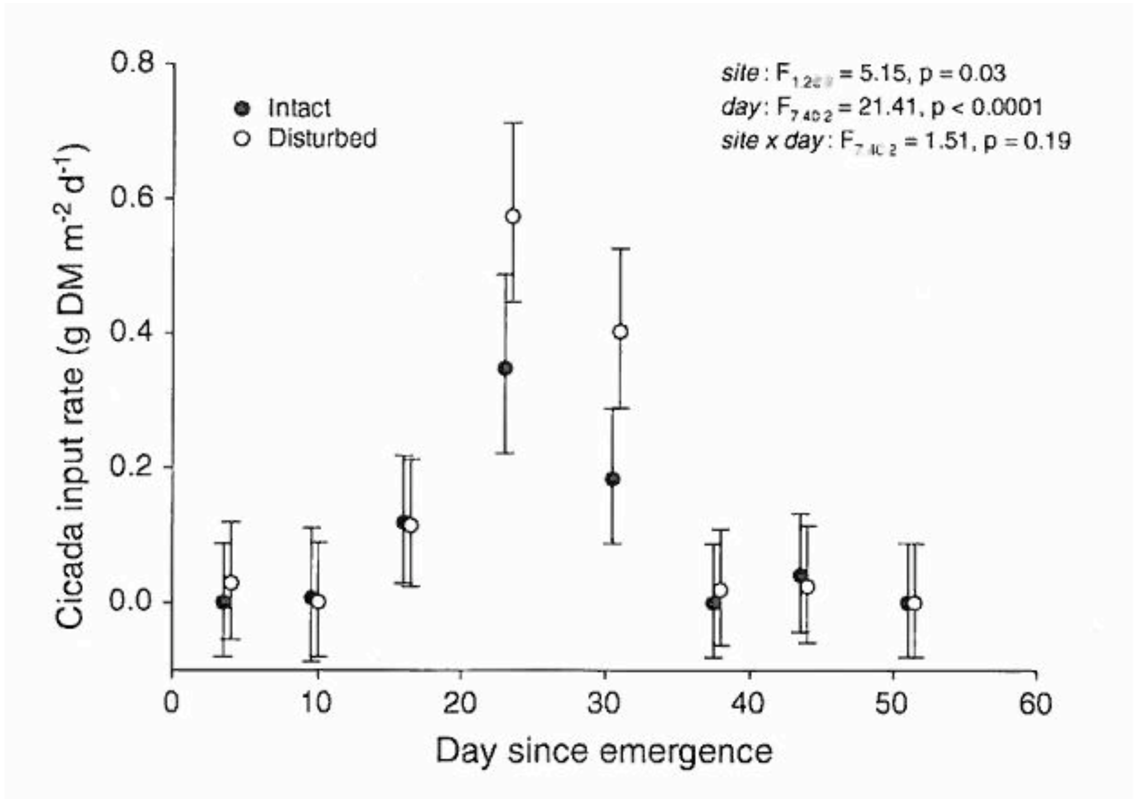

Figure 5: Graph of cicada input rates in intact (black circles) and disturbed (white circles) streams. Source: Menninger *et al*. (2008).

When examining the respiration prior to the cicada infestation, the intact stream had a respiration rate that was four times higher than that of the disturbed stream. Even with these differences in initial rates, there was a dramatic increase in respiration of both sites during the emergence period of the cicadas. It can be seen in Figure 6, that at their peaks, respiration nearly doubled at each site. The intact site reached its peak at day 26 and returning back to initial respiration outputs by day 40. This trend in respiration coincides with the peak input of cicadas into the environment.

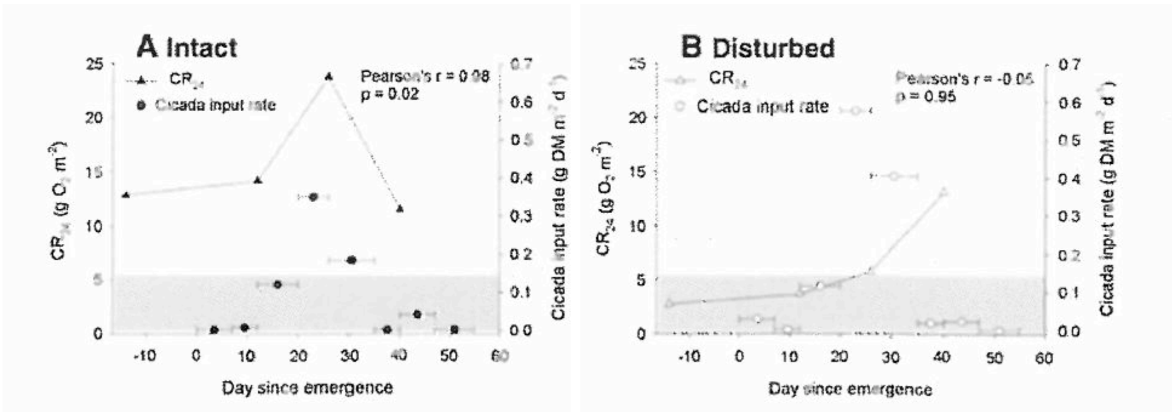

Figure 6: Graph of respiration over a 40-day time period in A) Intact and B) Disturbed environments. Source: Menninger *et al*. (2008).

The disturbed site displayed a different trend in both detritus input and respiration rates. Though there were lower numbers of insects per m^{-2} during emergence, there was a higher detritus input during the emergence time. This result is thought have happened because of the narrower riparian zone and newly planted trees near the stream offer suitable oviposition habitat for females to insert their eggs.

Seen in Figure 6, respiration rates in the disturbed stream do not appear to reflect the same trends as cicada input rates over the 40-day time span. The max respiration rate was found at the end of the field-testing. This delay in cicada decomposition is thought to have happened because of lower initial bacteria levels in the stream from the construction. Had the experiment continued past the 40-days it is hypothesized, based on others findings such as in Nowlin *et al*. (2008), that respiration rates would soon return back to original levels prior to the emergence.

Both sites showed no correlation between respiration and temperature increases. During the 40-day time of the study, the only factor that showed a significant correlation with stream respiration was the cicada input. There were no correlations with respiration and factors such as stream velocity, leaf litter, or temperature increase. Similar to findings in other aquatic experiments (Nowlin 2007), the mold and bacteria that were decomposing cicadas in streams were the same as the bacteria found in a pond environment.

3. Conclusion

The *Magicicada* species is a unique species that inhabits America. Through the species lineage, based on geographical regions, the species have diverged into several different sub-species (Cox 1991). What separates these sub-species from one another is their emergence periods. The trigger to these mass emergences of broods is uncertain but main theories believe that this trait is a result of responses to the ice age or a defense tactic. *Magicicada* emerges from the ground in such quantities that they satiate their predators and the bulk of the population survives to produce offspring for the next generation of cicada.

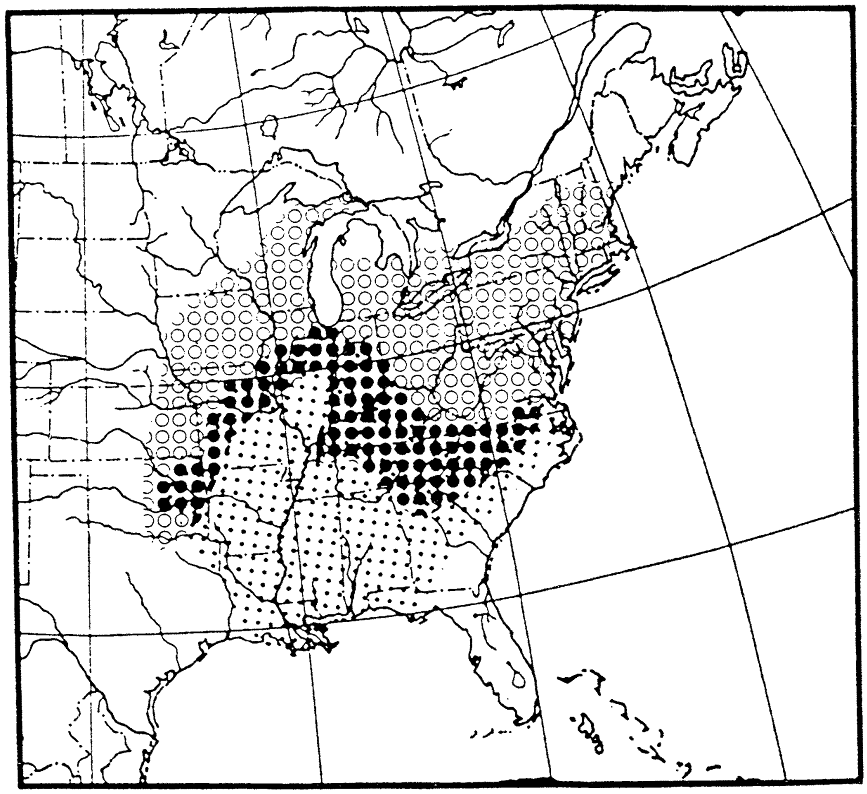

Figure 7: Map of the distribution 17- and 13 year cicada. 17-year cicada = open circles, 13 year cicada = small dots and 13 and 17 year = Large dots. Source Tom Cox, (1991).

During this resource pulse, animals will take advantage of the nutrient rich insect. Those animals that are foragers such as raccoons will capitalize on this abundance on the forest floors. The cicada offers an opportunity for foragers to use minimal effort to get what is an endless supply of food for the length of the emergence. Other animals display uncommon characteristics to feed on cicadas. The red-winged blackbird typically searches for food at a tree line, but when the chorus centers form deeper in the forest, the bird will venture into the forest to attain their meal. There is even a change in the birds eating habits while the insects emerged, over the course of the emergence the blackbird will go from consuming everything except the wings to solely eating the innards.

Though multiple predatorial species take advantage of the abundance of food, the cicadas main defense of predator satiation allows for a high percentage of the population to survive predation. Since cicadas will congregate for mating, most cicadas die near the chorus centers, because of this below ground nutrients is uprooted and deposited on the forest floor. This gives shallow rooted plants, such as the bellflower, an opportunity for better growth. The cicada carcasses are broken down to provide higher levels of nitrogen, potassium and phosphorus. Since nitrogen is believed to be the most limiting nutrient in plant growth, the resulting year shows an increase on in forest growth as an indirect result of the cicada species.

Magicicada that fall into streams and are not eaten by predators go through a similar process as those that fall to the forest floor. In aquatic environments, the carcass is decomposed quicker than on the forest floor. What typically takes a month in terrestrial ecosystems only takes one to two weeks in the water. The effects of the addition of cicadas in aquatic environments is easier to trace since the process occurs over a quicker period of time, as shown in Figure 6, a higher percentage of cicada nutrients is indirectly linked to aquatic predators.

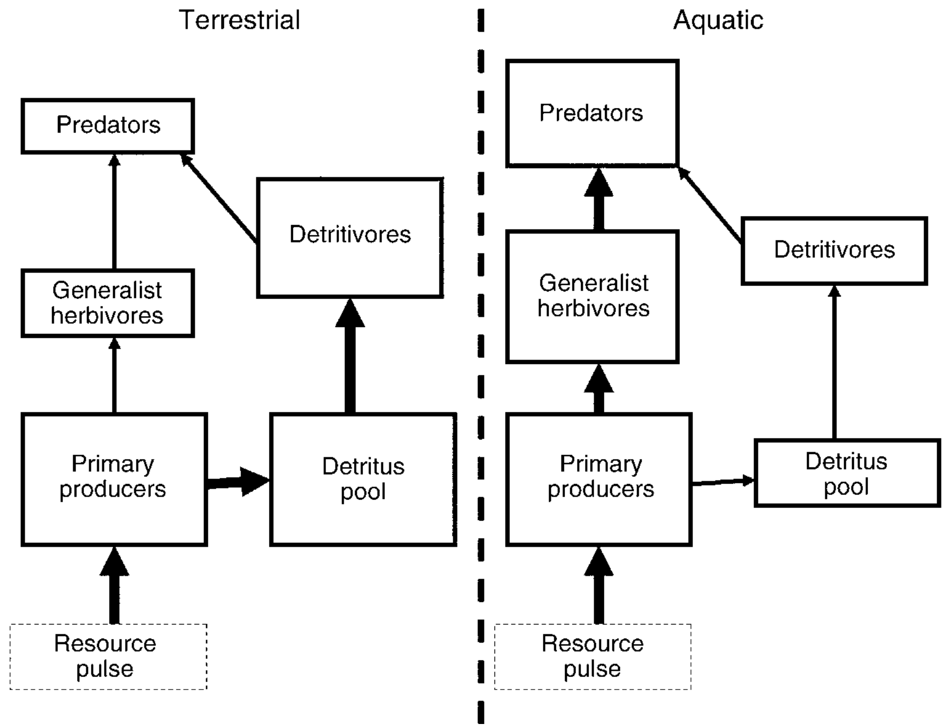

Figure 8: Web of pulse resource cycling in terrestrial and aquatic environments. Line thickness represents the effect that process has. Source: Nowlin *et al.*, (2008).

Uncertainties

As much that is known about the unique life and effects of the *Magicicadas* life and environmental impact, there is even more uncertainties that loom over the insect. Having such a unique life cycle, research on the insect is limited to only a few months every 13 or 17 years. The underground life span of the insect is one of the largest uncertainties of the insect. Aside from spending most of its life around tree roots and living off of xylem there is little that is known about this period of a cicadas life since they are hard to track.

Above ground there are also many uncertainties and problems which occur from these emergences. Understanding the behaviors of different predators, during this emergence poses problem. In research performed by Storm *et al.,* animals such as the gray squirrel were observed eating cicadas in the field, but the gray squirrels captured during the experiment revealed no trace of consuming the insect. There is also little known about aquatic predatorial habits (Vokoun 2000). Cicada influence on the aquatic environment is well-documented in bottom up effects, but there is little known about dietary changes of aquatic predators during a cicada emergence. Though there is sufficient research on how certain species react to the cicada emergence investigations are still needed to quantify how all animals will respond to this pulse resource.

There are many questions that are yet to be answered on predatorial impacts on cicadas, but the largest uncertainties lie with the *Magicicadas* influence on terrestrial environments. With millions of cicada nymphs acquiring nutrients from tree and plant roots, little is known about the effects that the nymph has on the growth and nutrient intake of these plants due to the insect feeding off the roots. Once the insect emerges it is understood that there is an immediate impact of nutrient cycling to the forest floor. There is observed growth over the next year in the forested areas where cicada detritus is prominent. What should be further examined is the long-term influence of this and other resource pulses in terrestrial environments (Nowlin *et al.* 2008). Most growth that is observed is in small-scale areas. Further research is necessary to understand how these small-scale impacts play in a large-scale role, such as seeing how a forest will react to a growth increase in a small region of the forest.

The resource pulses of *Magicada* in North America offer a unique opportunity that allows for certain species to thrive. Opportunistic animals and shallow rooted plants have been found to capitalize on the resource pulse. Cicada emergences can have a profound impact on the environment around them. Further research of what these impacts are can offer insight into how other resources pulses effect an environment. By attaining a better understanding of how environments react to these changes we are able to better predict how environments will react when faced with different adversities.

References:

Ahern, R. G., S. D. Frank, and M. J. Raupp. 2005. Comparison of Exclusion and Imidacloprid for Reduction of Oviposition Damage to Young Trees by Periodical Cicadas (Hemiptera: Cicadidae). Journal of Economic Entomolgy. 98(6): 2133-2136.

Alexander, R. D., T. E. Moore. 1962. The evolutionary relationships of 17-year and 13-year cicadas, and three new species (Homoptera, Cicadidae, *Magicicada*). Misc. Publ. Mus. Zool. Univ. Mich. 121: 1-59.

Christensen, H., M. L. Fogel. 2010. *Feeding Ecology and Evidence for Amino Acid Synthesis in the Periodical Cicada (Magicada)*. Journal of Insect Physiology. 211-219.

Cox, R. T., C. E. Carlton. 1991. Evidence of Genetic Dominance of the 13-year Life Cicle in Periodical Cicadas (Homoptera: Cicadidae: Magicicada spp.). American Midland Naturalist. 125: 63-74.

Grant, P. R. 2005. The Priming of periodical cicada life cycles. Trends in Ecology and Evolution. Vol. 20. 4: 169-174.

Krohne. D. T., T. J. Coulliard, J. C. Riddle. 1991. Population responses of *Peromyscus leucops* and *Blarina brevianca* to emergence of periodical cicada. American Midland Naturalist. 126:317-321.

Llyd, M., R. Karban. 1983. Chorusing Centers of Periodical Cicadas. J. Kan. Entomol Soc. 56:299-304

Marshall, D. C. 2000. *Behavior and evolution of periodical cicadas (Magicicada spp.)*. Thesis, The University of Michigan.

Marshall, D. C., J. Cooley, K. B. R. Hill. 2011. *Developmental Platicity of Life-Cycle Length in Thirteen-Year Periodical Cicadas (Heiptera: Cicadidae)*. Entomological Society of America. Annals of the Entomological Society of America. 443 – 450.

Menninger, H. L., M. Palmer. , L. Craig, D. Richardson. 2008. Periodical Cicada Detritus Impacts Stream Ecosystem Metabolism. Ecosystems. 11: 1306-1317.

Mumford, R. E., J. O. Whitaker, Jr. 1982. Mammals of Indiana. Indiana University Press. Bloomington.

Nowlin, W. H., M. J. Gonzalez, M. J. Vanni, M. H. H. Stevens, M. W. Fields, and J. J. Valente. 2007. Allochtonous subsidy of periodical cicadas affects the dynamics and stability of pond communities. Ecology. 88: 2174-2186.

Nowlin, W. H., M. J. Vanni, L. H. Yang. 2008. Comparing Resource Pulses in Aquatic and Terrestrial Ecosystems. Ecology. 89(3): 647-659.

Robinson, G. R., P. L. Sibrell, C. J. Boughton, L. H. Yang. 2007. Influence of soil chemistry on metal and bioessential element concentrations in nymphal and adult periodical cicadas (*Magicicada* spp.). Science of the Total Environment. 374: 367-378.

Simmons, J. A., E. G. Wever, J. M. Pulka, 1971. Periodical Cicada: Sound Production and Hearing. Science. 171: 212-213.

Speer, J. H., K. Clay, G. Bishop, M. Creech. 2010. The effect of periodical cicadas on growth of five tree species in Midwestern Deciduous Forests. American Midland Naturalist. 164 (2): 173-186.

Steward, V. B., K. G. Smith, F. M. Stephen. 1988. Red-winged blackbird predation on periodical cicadas (Cicadidae: *Magicicada* spp.): bird behavior and cicada responses. Oecologia. 76: 348-352.

Storm, J., J. O. Whitaker, Jr. 2007. Food Habits of Mammals During an Emergence of 17-year Cicadas (Hemiptera: Cicadidae: *Magicicada* spp.). Department of Ecology and Organismal biology. Indiana Academy of Science. 116: 196-199.

Vokoun, J. B., 2000. Shortnose gar (*Lepisosteus platostomus*) foraging on periodical cicadas (*Magicicada* spp.): territorial defense of profitable pool positions. American Midland Naturalist. 143: 261-265.

Wheeler, G. L., K. S. Williams, K. G. Smith. 1992. *Role of Periodical Cicadas (Homoptera: Cicadidae: Migicicada) in Forest Nutrient Cycles*. Elesvier Science Publishers. Forest Ecology and Management. 339-346.

White, J. and M. Lloyd. 1975. Growth rates of 17- and 13-year periodical cicadas. Am Midl Nat.: 94: 127-143

Williams, K. S., C. Simon, 1995. The ecology, behavior, and evolution of periodical cicadas. Annual Review of Entomology 40, 269-295.

Yang, L. H. 2004. Periodical cicadas as resource pulses in North American forests. Science. 306: 1565-1567.

Yang, L. H. 2012. Resource pulses of dead periodical cicadas in American bellflower rosettes under competitive and non-competitive conditions. Anthropod-Plant Interactions. 7: 93-98.