The Gypsy Moth: is Defoliation Dependant on Climate Factors?

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Abstract:

      The gypsy moth, *Lymantria dispar*, is one of North America's most devastating forest pests. It is responsible for millions of dollars in damage to forests and communities and it is subject to billion dollar management plans. The species is native in Europe and Asia and has existed there for thousands of years and survived the harsh climates related to those areas. In the United States, the gypsy moth is spreading with little opposition. Understanding the issue can lead to the solution of the problem. The specific data that should have the greatest effect on the gypsy moth is weather and treatment data. Climate can act as a limiting factor that can help explain the rise and fall of defoliation numbers. A variable like wind speed helps determine rate of spread and the variables precipitation and temperature can act as limiting factors. Understanding the effects of climate on gypsy moth populations may serve as a road map through which preventative measures can be employed in areas where the gypsy moth infestation may expand due to changes in climate. Climate data that was analyzed in 10 Wisconsin counties to determine a correlation between defoliation and climate, with two p-values under .05 I found that the correlation between my climate variables and defoliation was correlated with temperature. A more extensive study is required to better understand the connection between climate and defoliation.

Introduction:

      The definition of an invasive species according, to the Wisconsin DNR, is a non-indigenous species whose introduction causes or is likely to cause economic or environmental harm or harm to human health (WIDNR 2011). Most of these invasive species are harmless to the environment. However, there are some that are harmful and can cause widespread damage to the environment. Some of the ways these invasive species become problematic is when they either outcompete the natural species or they lack natural predators that keep the population in check.

      The gypsy moth, *Lymantria dispar*, is one such species. It is responsible for the defoliation of many of America's native trees causing the deaths of these trees and millions of dollars in damages. The species is native in Europe and Asia and has existed there for thousands of years. In 1869, Leopold Trouvelot accidentally introduced the gypsy moth near Boston, MA. About 10 years after this introduction, the first outbreaks began in

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Trouvelot's neighborhood and in 1890 the state and federal government began their attempts to eradicate the gypsy moth.

Humans are often inadvertently helping this invasive species. They are introducing them to areas where they have very little natural predators or competitors. With no natural predators a species can spread unchecked by the environment. In the case of herbivores, unimpeded growth of a population can cause horrendous damage to a food chain by taking away a large portion of the producers, which forms the base of most food webs. A food web is an interconnected set of food chains in the same ecosystem. Food webs make possible the transfer of energy from plants through herbivores to carnivores and omnivores, and ultimately to the detritivores and decomposers that enrich the soil with organic waste. When this occurs, in most circumstances, it can lead to a population crash because the depleted environment cannot support the large population numbers produced by the outbreak. In response, management solutions were put in place early on to attempt to control the gypsy moth, but the early methods of control lacked the knowledge of how the species were spreading and many of these methods failed. Every year isolated populations are discovered beyond the contiguous range of the gypsy moth but these populations are eradicated or they disappear without intervention. It is inevitable that the gypsy moth will continue to expand its range in the future. The spread mainly comes through the nursery trade, transportation of firewood, and other related human influenced movement.

Despite over 100 years of presence in North America, researchers are still at a loss to explain and predict the extent of the changes in forest vegetation likely to take place through gypsy moth disturbance. A major concern is the potential loss of economically critical and ecologically dominant oak species (Quercus, spp.). Approximately 75 percent of the nation's hardwood forests lie outside the current European gypsy moth quarantine area (APHIS). There could be huge potential problems if the moth is allowed to spread into these areas. Timber production would be negatively affected by gypsy moth defoliation. In addition, homeowners, landscape and Christmas tree enterprises as well as local governments would incur significant costs to suppress the pest population.

Unfettered spread of gypsy moth would result in severe environmental damage to forest vegetation and the wildlife that depend on the forest environment. Waterways would be adversely affected due to increased rates of erosion caused by accelerated runoff from the loss of vegetative cover. Increased incidents of flooding could occur downstream. Economic effects would also occur. Pesticide use would likely increase and over an extended time frame, could result in additional risks to human health and environmental quality.

Gypsy moth populations can grow quickly. Forest stand densities may fluctuate from near 1 egg mass per hectare to over 1,000 per hectare (Barbosa 79). When densities reach very high levels, trees may become completely defoliated. Several successive years of defoliation, along with contributions by other biotic and abiotic stress factors, may ultimately result in tree mortality. In most northeastern forests, less than 20% of the trees in a forest will die but occasionally tree mortality may be very heavy. Tree damage is caused by the insect larvae, or caterpillars, which emerge from their eggs beginning in early spring and continuing through mid-May. The larvae move to the leaves of trees and begin to eat, mostly at night. During daylight hours, larvae generally seek shade from the sun but feeding can occur in daytime in heavy infestations.

One key effect that the environment has on the spread and the suppression of the gypsy moth is climate factors like temperature, wind speed, and amount of precipitation. With these factors considered there is evidence that can support the theory of climatic limitation of the gypsy moth. The gypsy moth has been intensively studied over the last 100 years in North America. Currently there are numerous groups around the country investigating various aspects of the biology, ecology, and management of the gypsy moth. The USDA (United States Department of Agriculture) Forest Service, the USDA Agricultural Research Service, the USDA Cooperative State Research Service, the USDA Animal and Plant Health and Inspection Service, and numerous state and private universities fund this work. The above research, combined with the data sources at NOAA and the DOA, was used to determine the effect that climate and specifically precipitation, temperature, and wind speed have on the gypsy moth. These climatic data points can aid the authorities and me in understanding the spread and the limiting factors that they have upon the gypsy moth.
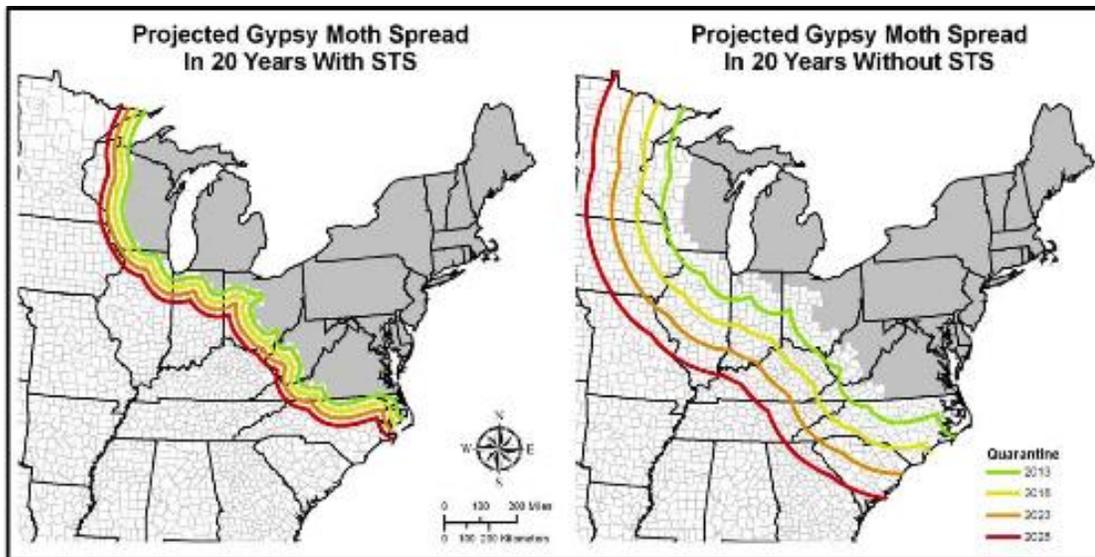
Literature Review:

Gypsy moth larvae grow by molting, five molts for males and six for females (GMSTS). Feeding occurs in the "instar" stage or period between each molt. As might be expected, a caterpillar's appetite increases with each molt. Feeding continues until mid-June or early July when the caterpillar enters the pupal stage and emerges, finally, as a moth. Both male and female moths exist only to reproduce once. The male moths fly around until they find a female who is too heavy to fly. After the females lay their eggs from July to September, depending on location, and then the moths of both sexes die.

The Gypsy Moth Program is an effective Federal-State partnership that prevents the establishment of gypsy moth in areas of the United States that are not contiguous to currently regulated States, counties, and townships. Within this partnership, the goal of APHIS-PPQ is to define the extent of the gypsy moth infestation and limit its artificial spread beyond the infested area through quarantine and an active regulatory program. Historically, conventional pesticides such as DDT, carbaryl, and acephate were used in the northeastern states in gypsy moth suppression/eradication programs. Non-target impacts and human health concerns resulted in discontinuing these products as suppression and eradication strategies for gypsy moth. Suppression eradication programs for gypsy moth typically involve an integrated pest management (IPM) approach. The regulatory program enables us to control the movement of gypsy moth host material from gypsy moth infested areas to other areas of the United States, thus limiting the artificial, or human-assisted, spread of the pest. An intensive trapping program allows us to monitor the populations of this pest. The results of the trapping program allow us to identify new populations of gypsy moth and take action before they are able to become established in uninfested areas. Some human actions benefit the spread of certain pest species including the gypsy moth.

Habitat fragmentation, such as building roads, and ditch digging, prevents other natural processes like periodical fires. When humans build these artificial barriers they fragment the habitat, which can lead to loss of biodiversity. Habitat fragmentation through the building of roads can alter the water runoff rate causing washouts as well as contributing to speciation of the native species. Humans often try to prevent fire from

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occurring naturally. When this occurs in areas where periodic fires are the regime, understory trees and brush build up. When the fire finally occurs, the understory which would be cleared by periodic fires build up and cause a canopy fire that burns for thousands of acres killing trees that would normally survive the periodic fires. From human activity an ecosystem that has been altered via roads or bad forestry practices will not be able to respond to an invasive species as well as a healthy one will.

Spreading invasive species to uninfested areas by not clearing ballast water, failing to remove invasive plants or animals on boats, or by transferring firewood from infested areas is also common (WIDNR 11). Humans are guilty of introducing more invasive species around the world whether or not they know it. Along with the introduction of invasive pest species comes the huge economic cost. In the United States, expenses associated with ecological damage and control of invasive species is estimated at $137 billion per year and is increasing (Pimentel 2001). Figure 1 shows that the spread of the gypsy moth would increase significantly with lack of management. This would result in more money being needed to slow down the spread. Although the shock value of a large economic cost is a powerful tool, another cost of invasive species is the social cost. What this means is that the invasive species can alter the ecosystem's ability to provide services like producing goods from a forest such as lumber or the ability to naturally cycle nutrients and other essential services.

Projected Gypsy Moth Spread In 20 Years With STS | Projected Gypsy Moth Spread In 20 Years Without STS

Quarantine
— 2013
— 2018
— 2023
— 2028

Grey shaded counties are infested as of 2008. Colored lines represent the predicted boundary of the gypsy moth quarantine over the next 20 years, with and without the STS Project.

Figure 1 - Depicts the effect that the STS (Slow the Spread) program will have on the gypsy moths' spread over the next 20 years. The grey area depicts the present range of the gypsy moth.

One goal of Environmental Science is to preserve biodiversity. This means at the very least preserving the base level producers as well as the keystone species through which the ecological community replenishes itself. The removal of one or more species in an ecosystem through invasive species competition can cause the collapse of the ecosystem. Because of this, about 42% of the species on the federal threatened or endangered species lists are at risk primarily because of invasive species (WIDNR 11).

Gypsy Moth Introduction:

Of these invasive pest species, the gypsy moth (*Lymantri dispar*) is one of the most destructive. An artist named Mr. L. Trouvelot, in a misguided attempt to breed a hardy silkworm, brought the gypsy moth to North America in 1869. Some escaped and the first recorded defoliation by gypsy moths was in 1889 of the trees in Trouvelot's own neighborhood of Medford, Massachusetts (UWEX 2011). From this start the gypsy moth has expanded its range due to the lack of natural predators and help from humans transporting logs that are infested with gypsy moth eggs.
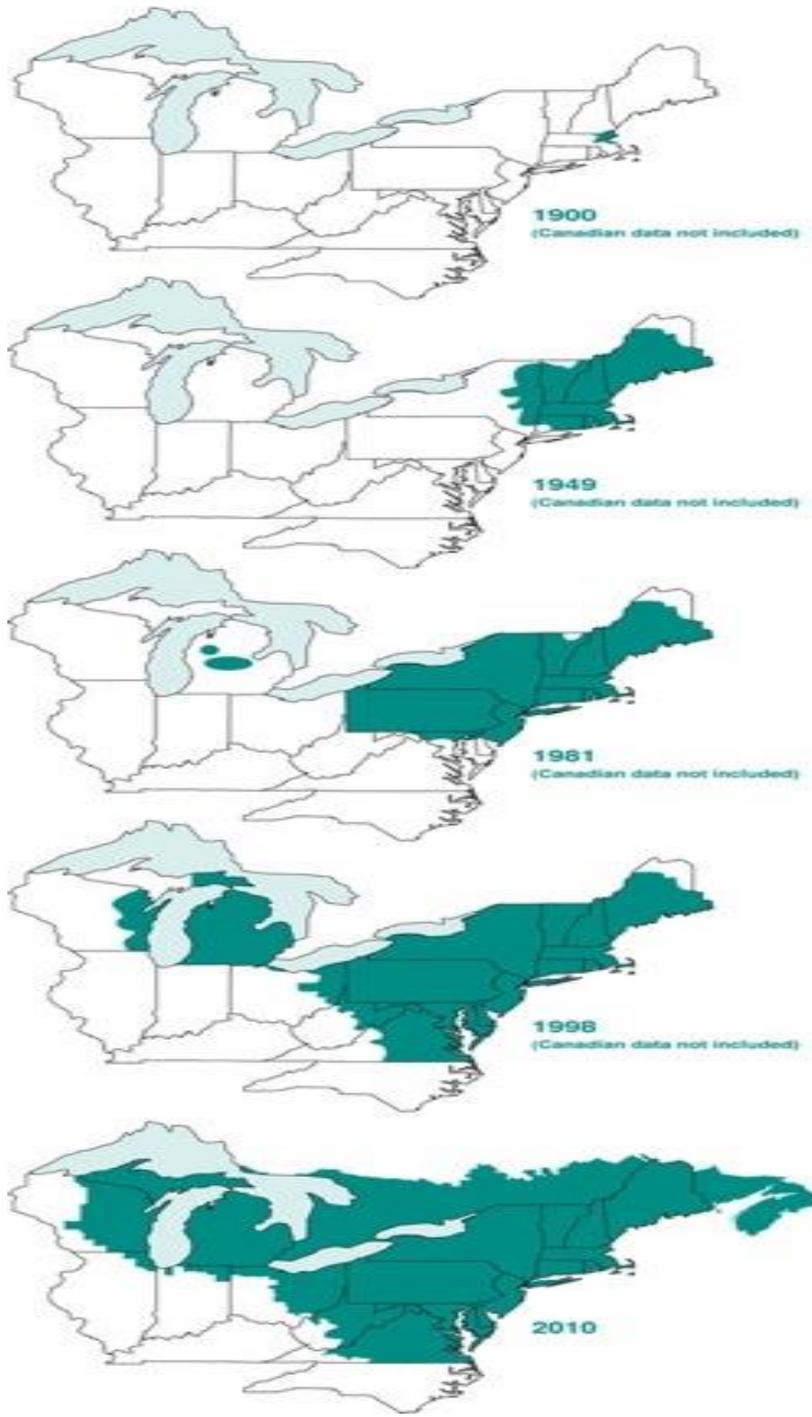
Figure 2 - The spread of the gypsy moth over time from 1900 to 2010.

The gypsy moth has been able to spread across the United States for many reasons: In its native range, gypsy moths can be found from the frigid Russian steppes to the subtropical shores of the Mediterranean. The eggs of the gypsy moth are the over wintering phase and can withstand freezing temperatures until they hatch in the spring. The gypsy moth is not picky about what it eats; it has been recorded feeding on over 300 species of trees and shrubs (UWEX 11). The gypsy moth is currently spreading at a rate of about 21 km / year along the borders to the north (southern Canada), west (Minnesota and Illinois), and south (Virginia and Ohio). Since females are not capable of flight, this spread can be attributed to natural movement of wind-borne, 1st instar larvae and accidental movement of life stages by humans (USFS 2003). The gypsy moth causes the most destruction in the summer months when the caterpillars are present. These caterpillars can occur in great numbers, which cause widespread defoliation of trees in the area of the outbreak. Population densities vary by several orders of magnitude, often reaching epidemic densities that have spectacular effects (i.e., total defoliation of host trees). It is not uncommon for gypsy moth populations to persist for many years at densities so low that it is difficult to detect any life stages (Liebhold 2000). The timing of outbreaks is irregular and difficult to predict, although there is some statistical evidence of a 10- to 11-year cycle in outbreak dynamics (Leibhold 2000). This population cycle for the gypsy moth is similar to the boom and bust cycles of other defoliating insects.
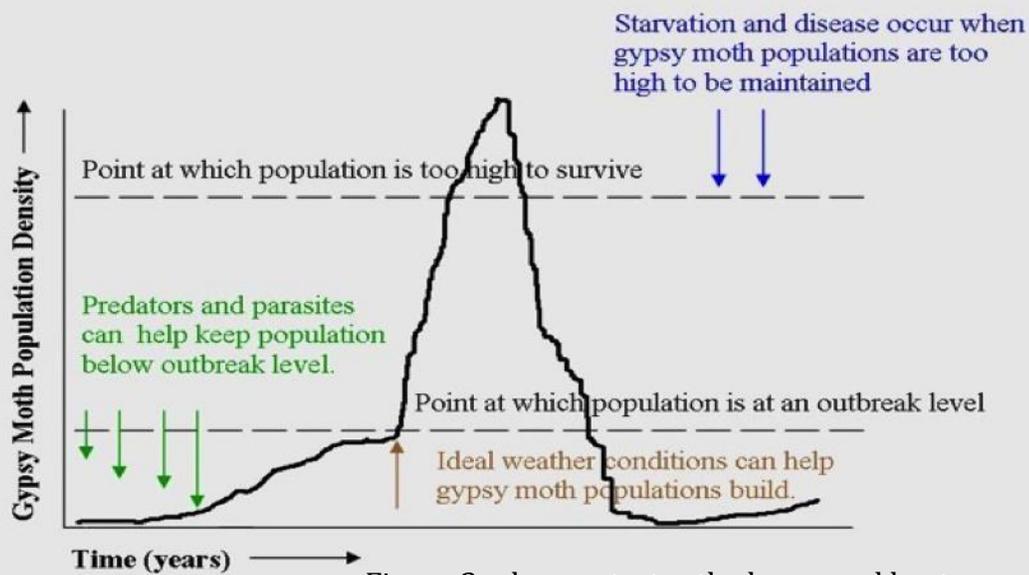
Figure 3 - demonstrates the boom and bust

model of which the gypsy moth follows.

Figure 3 shows the gypsy moth life cycle. When a gypsy moth population is established and small, the natural predators can keep the population under control. Soon the population slowly grows due to available food and begins to reach the outbreak level. When the conditions are right the population can increase greatly and will continue to rise until the available food runs out. It usually takes only one to three years before starvation, disease, and natural enemies cause the population to return to low levels, but in the meantime damage is done to trees (UWEX 11).

Climatic effects on the Gypsy Moth:

The gypsy moth (Lamantria dispar), like many invasive species, is affected by the climate. The most important of these climactic variables can act as limiting factors like temperature and precipitation. Studies have shown that a gypsy moth egg mass can be rendered unviable in temperatures lower than 20°F (Andersen). Other climatic variables like wind speed aid in the dispersal of the moth. With these variables there is the possibility to better understand how the gypsy moth and other invasive species are affected by various climate factors.

Temperature is one of the main climatic variables that control many aspects of the invertebrate life cycle. Temperature plays an important part in the life cycle of insects. Many insects die during the colder winter months. If temperatures should increase by just a couple of degrees, a number -- perhaps a significant number -- of these insects won't die.

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This could lead to a jump in insect population (HSW). The effects of increased temperature due to climate change is leading to the further spread of the gypsy moth's range. This is true especially to the North where low temperatures in the past have helped slow the expansion of the moth. A model of the insect's seasonality was used to predict the probability of its establishment in Canada (U of I Ext.). The model predicted that this species, which is highly polyphagous, or has a highly varied diet, would threaten considerable hardwood forest resources as climate change allows it to expand further north and west into Canada. It is estimated that the proportion of Canada's deciduous forests at risk of damage by gypsy moth will grow from the current 15 percent to more than 75 percent by 2050 (U of I Ext.). The hatching of gypsy moth eggs synchronizes with budding of most hardwood tree species. Larvae emerge from the egg masses from the early spring to mid May. There can be a significant effect of temperature on a gypsy moth egg mass. Studies have shown that a gypsy moth egg mass can be rendered unviable in temperatures lower than 20°F. Egg masses on southern and western aspects, where solar loading and temperatures were greatest, experienced substantial mortality. Mean survival of eggs averaged across the three seasons was less than 25% on southern and western aspects, compared with averages of 53 and 73% on eastern and northern aspects, respectively. Snow cover moderated egg mass temperature, with extreme seasonal minimum winter temperatures under snow cover as much as 7.1 °C warmer than those without snow cover (Andersen). The gypsy moth usually lays its egg masses on the trunk of a tree about half way up to about 2 feet above ground level. This allows for the egg masses covered by the snow in higher latitudes to be insulated and allows for greater survivability in cold temperatures.

Another climatic factor that is important to note is the wind speed. The wind is important to the gypsy moth because it is the natural method of dispersal for the species. Natural dispersal occurs when newly hatched larvae hanging from host trees on silken threads are carried by the wind for a distance of about 1 mile. Larvae can be carried for longer distances (McManus). The wind speed and direction are also key in the reproduction of the gypsy moth. The wind carries the pheromone from the female moth to the male, which is the only moth that is able to fly. There is reason to believe that Gypsy Moth larva

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are able to cross significant geographic obstacles such as Lake Michigan. Such dispersal events seemed to have occurred in the mid- to late-1990s with spread across Lake Michigan to Wisconsin. Such dispersal would be against the prevailing wind flow for the area and would have crossed a significant physical barrier Lake Michigan. The climatology of the region shows that vigorous cyclones can result in strong easterly winds in the area at the time when early instars are present (Frank). This spread can explain some non-anthropogenic dispersal patterns. The final climatic factor that is important for gypsy moth survivability is precipitation. Rainfall can drown larva before they are established, low populations are correlated to heavy rainfall during the larval stage. Rainy weather inhibits dispersal and feeding of the newly hatched larvae and slows their growth (McManus). Another aspect of the rain is how it helps the spread of various diseases that affect the gypsy moth such as NPV and E. Maimaiga. Bioassays using larvae in mesh bags on originally contaminated branches and branches below indicated that rainfall is effective in moving virus from branch to branch. This result was confirmed by an experiment using similar methods and naturally occurring rainfall (D'Amico). The other disease is a fungus, E. Maimaiga, that was introduced to control the gypsy moth. The life cycle of E. Maimaiga closely parallels that of the gypsy moth. The fungus over winters in the soil in the form of dormant resting spores. As springtime temperatures and moisture levels reach proper levels, (usually about 2 weeks prior to gypsy moth egg hatch) the resting spores germinate

and begin forcibly releasing fragile, short-lived conidia (active, infectious spores). Coming in contact infects caterpillars with soil borne resting spores or the germinating conidia. An enzyme helps the fungus penetrate the larva's body. Disease develops in the caterpillar, resulting in death within 7-10 days. Adequate moisture is key to the biology and pathogenicity of E. Maimaiga. This water dependence can be seen in two of the fungus' important processes. In the spring, resting spores germinate best 1-2 days after precipitation because high humidity (approaching 100%) is required for conidial development and discharge. Also, conidia production from dead larvae usually occurs on days
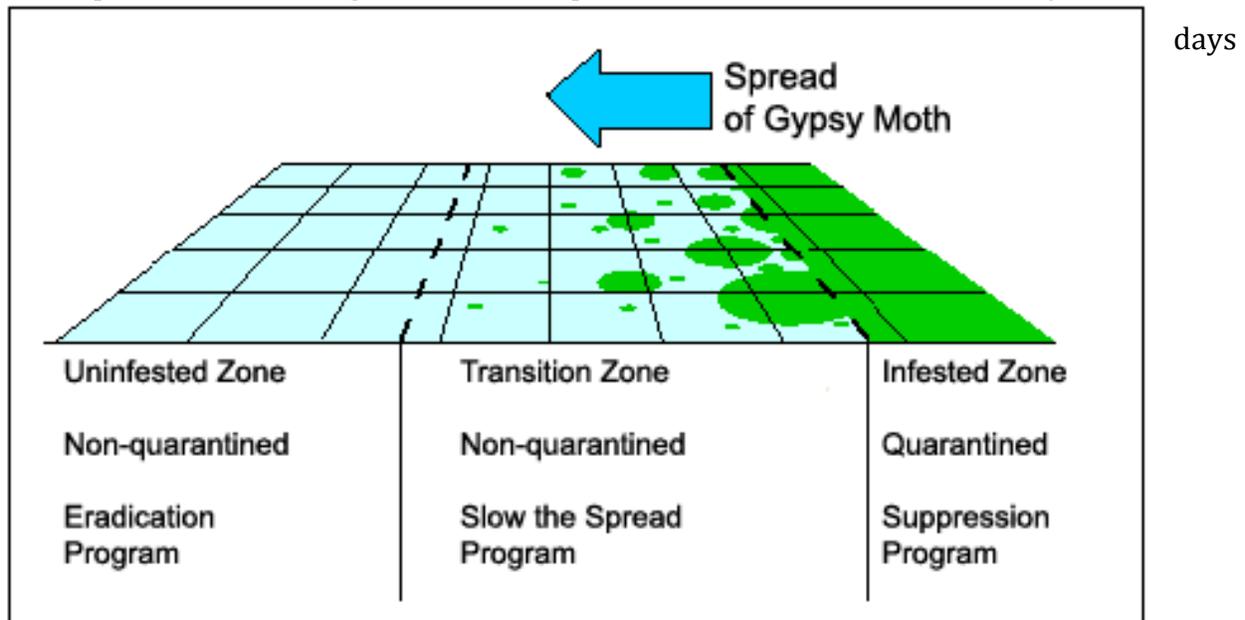

Diagram provided by the STS Decision Support System

when there is rainfall because free water is needed for conidial germination (ODNR).

Figure 4 - shows the three zones of the STS (Slow the Spread) method of which the Gypsy Moth is apart.

Management of the Gypsy Moth

As the gypsy moth spreads across North America the federal government has implemented programs of quarantine and eradication in the infested range to help contain and slow the spread of this invasive pest. The models that the state of Wisconsin has adopted are The Slow the Spread Program, The Suppression Program, and The Eradication

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Program. Figure 4 The project, as a whole is known as a barrier zone. A barrier zone can be either stationary or moving. If the barrier zone moves in the direction of population expansion then it will be slowing the rate of spread. Slowing the population spread may be substantially less expensive than stopping the spread. The benefits from slowing the spread of a pest species result from the delay in colonization of currently uninfested areas (Sharov 1998). The Slow the Spread program tracks the boundary of the transition zone by collecting data from pheromone traps counting the number of male Gypsy Moths. With knowledge of the areas that have been colonized in the uninfested and transition zones, appropriate steps may be made to use insecticide. Male moths are the primary population indicators, because the other life stages are rarely found (GMSTS 2007).

The Suppression Program is put into effect on the state and county level with support coming from federal agencies. Most of the negative impacts associated with the gypsy moth occur at high densities. Therefore, a common approach to gypsy moth populations is the direct suppression of populations in order to minimize these effects. These efforts are sometimes carried out by individual homeowners using ground applications of pesticides to individual trees, aerial application of pesticides by private contractors, or aerial applications of pesticides in cooperative state/federal programs (USFS 03).

One of the ways to predict how the gypsy moth will spread is to evaluate the stand dynamics outside of the transition zone and compare it to the area where the gypsy moth has been and compare the two habitats. For example it is known that the preferred tree species of the gypsy moth is the Oak (Barbosa 1979). If it were found that number of Oak stands increases, for example, in western Wisconsin it would be a good hypothesis to say that with an increase in Oak trees the speed of spread and the number of gypsy moth larva would increase. This area of Wisconsin is known as the drift less area. The abundance of preferred species that are crooked, low in vigor and with deep fissures in the bark as well as favorable site characteristics (ridge tops with shallow to bedrock soils, steep south and west facing slopes) will provide abundant food and habitat to the gypsy moth. These factors are expected to promote heavy gypsy moth defoliation in this region. These factors will also allow population on south and west facing slopes to increase and disperse to higher quality sites (lower north and east facing slopes) in the region (WIDNR 1997).

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In recent years the possibility of using biological control has been studied and has potential. Since the gypsy moth is an invasive species it has very few predators in its introduced environment, which has allowed it to spread so far. One of the natural predators of the gypsy moth is the white-footed mouse or deer mouse. This rodent relishes gypsy moth pupae and will also attack the large caterpillars, skinning and gutting them before feasting. Deer mice can have a dramatic effect on the growth of gypsy moth populations. Evidence of their effectiveness can be seen by comparing defoliation of oak trees growing in lawns to those growing in a woodland setting with shrubbery, logs and other cover for mice (UWEX 11).

Another important predator species of the gypsy moth are birds. Chickadees and nuthatches will peck at egg masses in winter to extract eggs. Few birds will prey on the caterpillars as the long hairs irritate the thin skin around their eyes. However, some species with longer beaks do feed on the caterpillars. Cuckoos (black and yellow-billed) will congregate where hairy caterpillars such as the gypsy moth are abundant, but they can't eat enough to bring a population outbreak under control. Insects are predators of the gypsy moth as well. Beetles and other invertebrates can be important predators on the gypsy moth. The big, fast ground beetles kill many caterpillars that they find in the treetops, on the trunks, or on the ground. Stinkbugs inject a digestive fluid into the caterpillars that turns their tissues into a soup, which the stinkbug then ingests. And though they appear frail, daddy long-legs are predators with a poisonous bite and kill many pupae (they pose no threat to humans)(WIDNR 11).

Other methods of biological control involve fungi that target the caterpillars and another is the nucleopolyhedrosis virus (NPV). This is a naturally occurring virus that only infects gypsy moth. The virus is ingested by caterpillars and then destroys the internal organs of the insect (UWEX 11). This is one of the ways that biology can prove as an effective control of the gypsy moth. Another method of bio-control is the Btk (Bacillus thuringiensis) bacterium. Btk is a strain of common soil bacterium that occurs naturally. Btk is cultured by fermenting grains and potatoes with fish or corn meal, similar to brewing beer. The final product contains 90% water, the leftover growth medium, carbohydrates, inert ingredients approved as food additives, and the active ingredient (WIDNR 11).

Eradication programs are initiated in the west if multiple male moth catches of the North American strain occur within detection or delimitation trapping grids or other life stages of the insect is found. If a single Asian Gypsy Moth adult is captured, current APHIS (Animal, Health Plant Inspection Service) policy is multiple applications of Bt within a one-mile radius of the positive catch site.

Another form of treatment is known as mating disruption. This method of control is used to confuse the gypsy moth males, which will follow the scent to a female. The effect of this pheromone is irresistible to any male, who will come to find the source. The idea of mating disruption is to mimic the pheromone and spray it over an area so the male gypsy moths can't find the pheromone of the female over the synthetic pheromone. This method can be applied 2 ways both by aircraft. The active ingredient is sandwiched between two layers of extremely thin PVC plastic, which are then chopped up into tiny pieces. The pheromone is slowly released from the flakes after it is applied. Flakes will degrade over time and at such small amounts, have not been shown to accumulate in the environment (MDA 2008). The second method utilizes wax; the active ingredient is mixed into a waxy matrix that is applied as a tiny droplet. The pheromone is released into the air after the droplet is applied. Wax will break down over time and has not been shown to accumulate in the environment (MDA 2008).

The focus of trying to control the damaging effects of the gypsy moth through chemical or biological means is not always the best option. While major outbreaks can defoliate entire areas the survival of the tree species affected is important and takes place in the long-term spectrum. Silviculture is the practice of controlling the establishment, growth, composition, health, and quality of forests to meet diverse needs and values. These silvicultural methods of control are important for the survival of urban trees, which are under stress already. Trees in an urban setting are under stress due to the combination of limited root space, increased contact with humans is a variable that could result in many negative outcomes. Trees under stress will fall victim to many of the many diseases and parasites that a healthy tree would repel. Because trees are long-lived and slow growing, forest management practices are most effective when applied well in advance of gypsy moth defoliation. Land managers can minimize the ultimate impact of gypsy moth defoliation by starting now

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Table 1. Gypsy Moth Host Preferences (33)

Category	Overstory species	Understory species
Preferred Species readily eaten by all caterpillar stages.	All oak, bigtooth and quaking aspen, basswood, paper and river birch, larch, mountain-ash, tamarack, willow and apple	Hawthorn, hazelnut, hop hornbeam, hornbeam, and serviceberry
Less preferred Species fed upon when preferred species are unavailable and by older caterpillar stages.	Yellow birch; box elder; butternut; black walnut; sweet and black cherry; eastern cottonwood; American, Siberian** and Chinese elm; hackberry; hickory; Norway**, red and sugar maples; all pine; all spruce; buckeye*, and pear*	Blueberries, pin cherry, chokecherry, sweet fern
Avoided Species that are rarely fed upon.	All ash, E. red cedar, balsam fir, silver maple, slippery elm, N. catalpa*, Kentucky coffeetree, horse chestnut*, sycamore*, black** and honey* locusts and red mulberry**	Dogwood, elderberry, grape, greenbrier, juniper, mountain and striped maple, raspberry, viburnum, and buckthorn**

*   Commonly planted urban species. Use in woodlands is not recommended.
** Species that can be invasive. Gypsy moth defoliation may increase their competitive edge if left in a managed stand.

Table 1 - (Gottschalk 1993) Table 1 shows the preferred host species of the gypsy moth larva.

(MDNR 2009). Management options for the control of the gypsy moth through sivicultural methods have two choices. The first involves reducing the likelihood of defoliation by reducing the percent of preferred host species found in a stand. This strategy is appropriate where the importance of non-host species can be increased, while still maintaining adequate stocking levels of important preferred host species. Doing so reduces the severity and frequency of gypsy moth population outbreaks, which in turn lessens the impact on recreation and aesthetic values. In stands with a 50% or more preferred host species composition, or in stands where site conditions or land use limit silvicultural options, diversifying the stand may not be an option. The second strategy is to reduce the vulnerability to mortality associated with gypsy moth defoliation-related stress by increasing stand vigor. Generally, damaged and suppressed trees are removed. Crop trees

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are favored. Non-preferred host species are encouraged where appropriate and healthy preferred host species are maintained as an important component of the stand (MDNR 09).

Climate can act as a limiting factor that can help explain the rise and fall of defoliation numbers. A variable like wind speed helps determine rate of spread and the variables precipitation and temperature can act as limiting factors. My first hypothesis for the effect of precipitation on defoliation is that defoliation would decrease as the amount of precipitation increases due to the effect precipitation has on limiting gypsy moth defoliation. The next hypothesis that defoliation would increase as average wind speed increases because wind acts as a natural dispersant for gypsy moth larvae. The third and most interesting variable is the relationship between temperature and defoliation figures. As temperature increases the defoliation number should increase. As temperature increases the activity of insects such as the gypsy moth increases leading to more defoliation. Climate data that was analyzed in 10 Wisconsin counties to determine a correlation between defoliation and climate, I believe that climate has a measurable effect on the amount of defoliation that occurs. Understanding the effects of climate on gypsy moth populations may serve as a road map through which preventative measures can be employed in areas where the gypsy moth infestation may expand due to changes in climate.

Methods:

The data was collected from 10 counties across Wisconsin measured by various types of weather stations. Wisconsin serves as an interesting area due to the presence of gypsy moth and the control strategies that comes with. The counties in question were Kenosha, Walworth, Dane, Sauk, Columbia, Marquette, Oconto, Marinette, Waushara, and Juneau counties. These counties in Wisconsin were chosen due to the limited defoliation data that was at my disposal. These counties were selected by the proximity of weather stations as well as the presence of defoliation data within the county in question. Wisconsin is an interesting case due to the fact that the gypsy moth front line is half way across the state. The climate data and information gathered was from the NOAA (NCDC) National Climate Data Center website. This data came from Quality Controlled Local Climatological

Data (QCLCD) and was compiled from 2005-2012. These different types of weather stations are AWOS- Automated Weather Observing System, MAPSO- Microcomputer-Aided Paperless Surface Observations, and ASOS (NWS)- The Automated Surface Observing Systems. These stations are located around airfields, regional or county airports, where they are used to collect hourly weather data. The data is collected from these stations automatically, which are 1.5m from the ground to accurately measure the climate variables. The data is then recorded and compiled by NOAA on their NCDC website and came in forms of hourly data for a month as well as summarized monthly data. The monthly summarized data was placed in a excel spreadsheet while the hourly data required more modification. The counties where this data was collected hourly was Baraboo and Juneau counties in Wisconsin. The variables that were collected were annual average temperature (measured in degrees F), annual average wind speed (measured in MPH), and total annual precipitation (Measured in inches.). Other variables used monthly average temperature included specific months April and July, which coincide with April hatching and July laying seasons. As well as a yearly average temperature figure which used a 1-year lag. The one year lag was to determine if the temperature during the laying of the egg. The measured value for precipitation was water equivalent, which by definition is the product of the mass of a body by its specific heat equal numerically to the mass of water that is equivalent in thermal capacity to the body in question (MW). The variable water equivalent was chosen to represent precipitation in all seasons meaning snowfall and rainfall. The reason I chose these statistics to compare with the defoliation data was the effects that each of the three variables has on the gypsy moth larva and their spread. The primary data set that I was comparing to the NCDC weather data was gypsy moth defoliation figures from the DOA (Department of Agriculture) by county. This defoliation data came in yearly summaries from 2008-2010. These datasets are collected from teams in the air that estimate the defoliation in acres, to be used in government studies to help predict and mitigate problems related to the gypsy moth pest. In some instances there was no data to be found for a target county this was primarily due to it being beyond the gypsy moth quarantine line where defoliation hasn't occurred.

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These datasets were compared and contrasted to determine if a correlation was possible. Some of the sites that had defoliation data didn't have a weather station in county that I could recover data for in which case I used the closest possible station. Finding the closest possible station to the source and then making sure that the distances were not above 50 miles from the county in question did this. After the data was collected it was compiled in Microsoft Excel and using the equation function I averaged and summed the hourly NCDC data and added it to the spreadsheet. After the data is organized into the columns and separated to only show the years with defoliation data the regression was run. In some cases there was very little defoliation data to go on I had to choose the counties that posted data. While it is nice to have more data to work with to make the experiment work I needed to put together what little I could gather.

Results:

The graphs that were created with the data that I gathered contained points that represent the y-axis are defoliation figures for a specific county and year, while the x-axis represents the climate variable that is being compared. The measurements that were taken and analyzed are average annual temperature, average annual wind speed, and total annual precipitation or (water equivalent). Other variables used monthly average temperature included specific months April and July which coincide with April hatching and July laying. As well as a yearly average temperature figure which used a 1-year lag. The defoliation data that I collected when organized trended towards a decrease in total defoliation. The P-values of the regressions show two of my six variables have p-values of less than .05 which indicates correlation. These two variables were Temp-1 and July egg laying, all of my other climate variables have a poor p-value. Both of the variables that showed correlation used a 1-year lag for average temperature. There are three outlier defoliation figures for Marinette, Sauk, and Columbia counties. These counties experienced a gypsy moth population explosion during the year the defoliation data was collected; this could explain the outliers in the data. There is a pattern with the temperature variables that shows defoliation decreasing when temperature increases. This trend is absent in the April
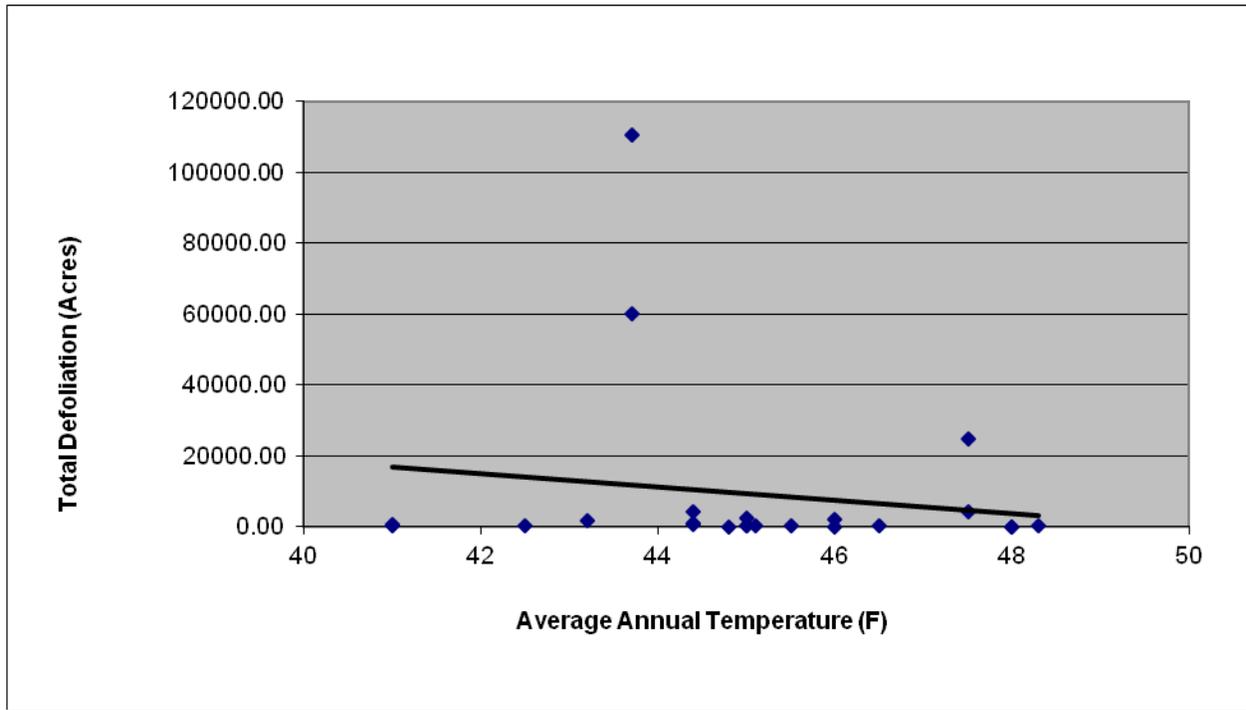
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hatching dataset.

Figure 5. Shows total defoliation in acres vs. annual average temperature in degrees Fahrenheit. The unusually high defoliation numbers are Marinette, Sauk, and Columbia counties. P-value = .50 R squared = .02166
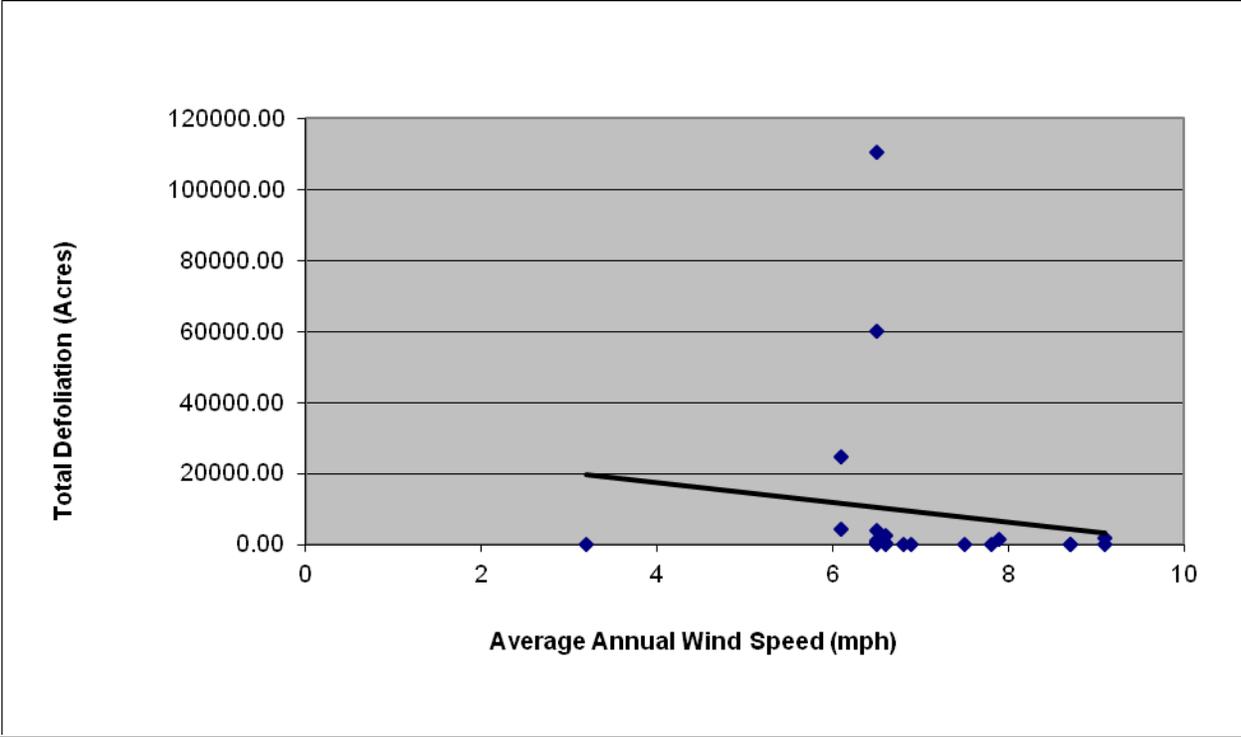
Figure 6. Shows total defoliation in acres vs. average annual wind speed in miles per hour. The unusually high defoliation numbers are Marinette, Sauk, and Columbia counties. P-value = .52 R squared = .0197
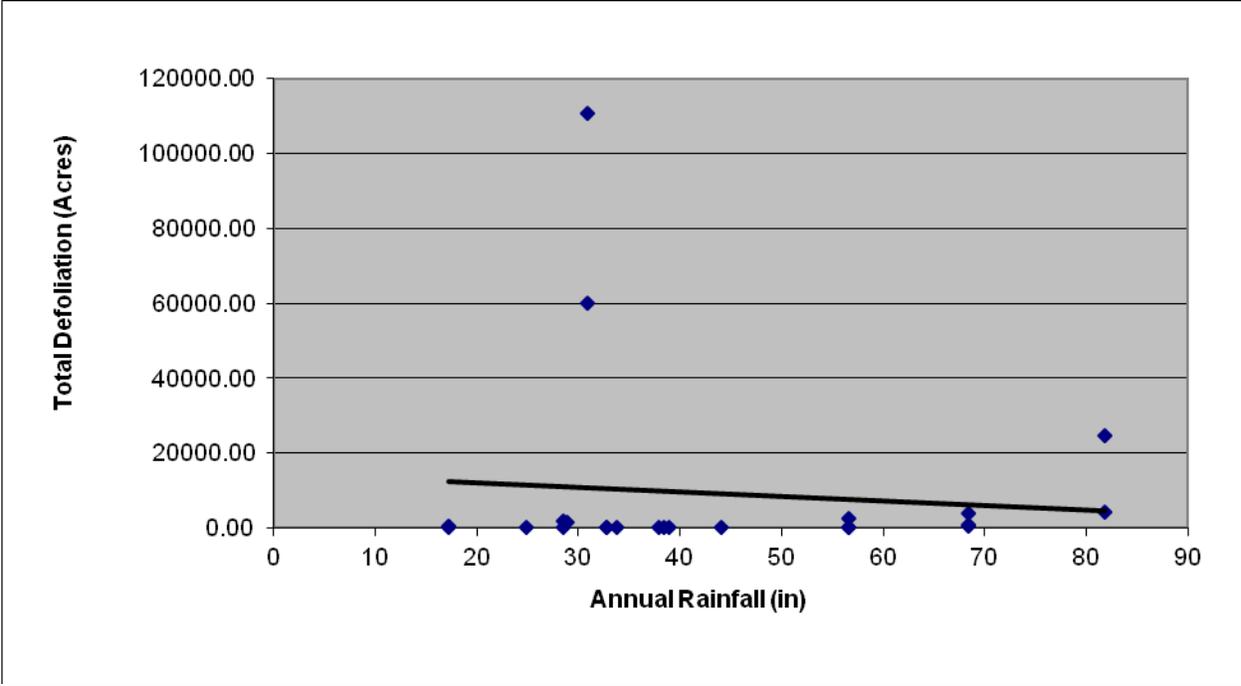
Figure 7. Shows total defoliation in acres vs. total annual precipitation in inches. The unusually high defoliation numbers are Marinette, Sauk, and Columbia counties. P-value = .68 R square = .00803
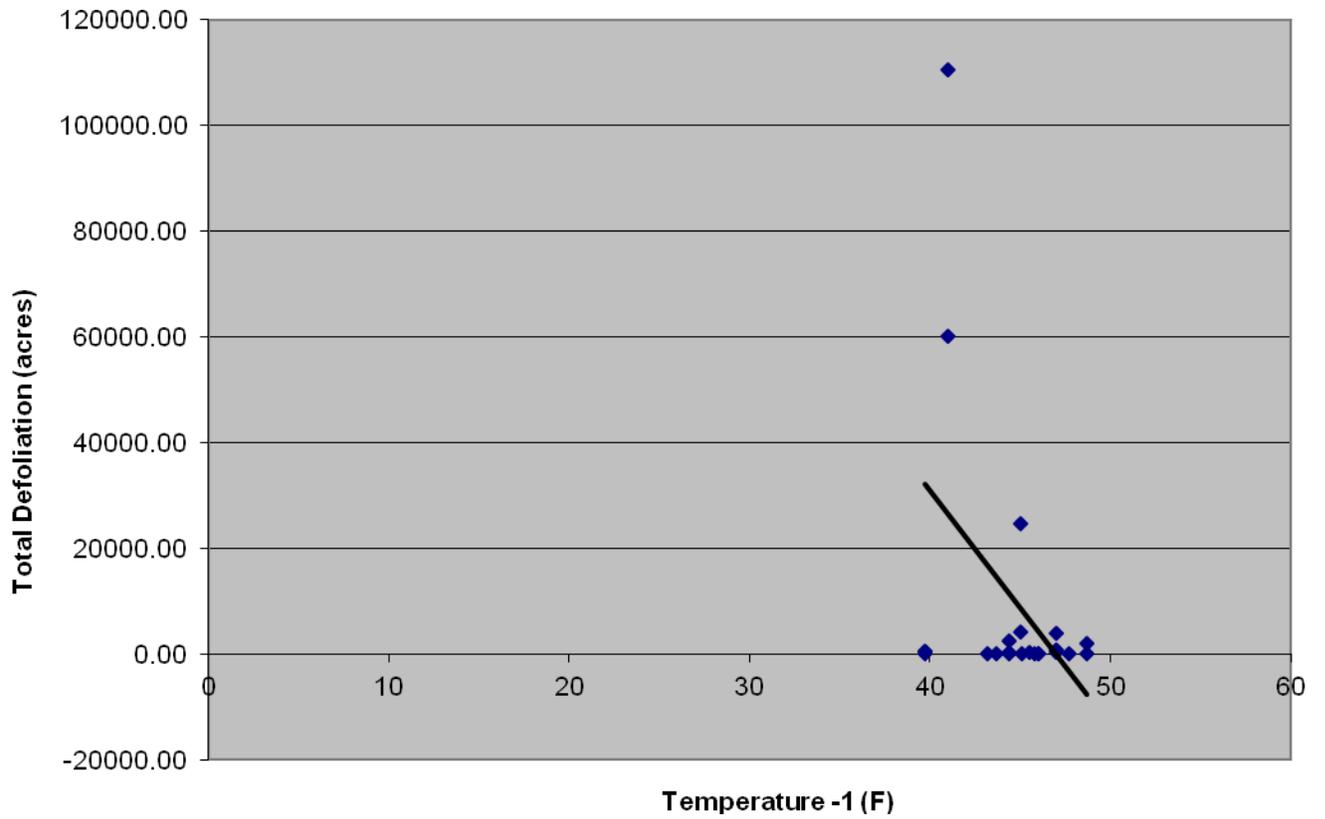
Figure 8. Shows total defoliation in acres vs. annual average temperature in degrees Fahrenheit. The yearly average temperature was recorded with a 1 year lag. The unusually high defoliation numbers are Marinette, Sauk, and Columbia counties. P-value = .04 R squared = .19
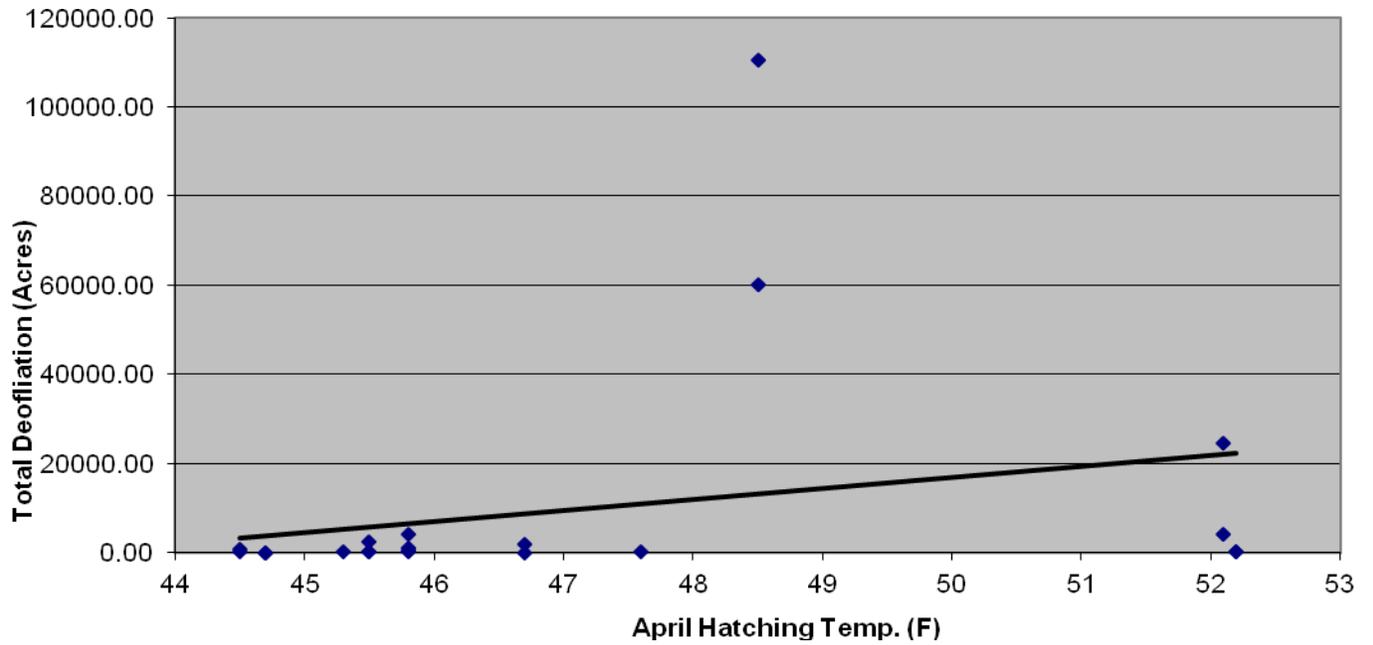
Figure 9. Shows total defoliation in acres vs. annual average temperature in degrees Fahrenheit in the month of April, which coincides with gypsy moth eggs hatching. The unusually high defoliation numbers are Marinette, Sauk, and Columbia counties. P-value = .248 R squared = .06
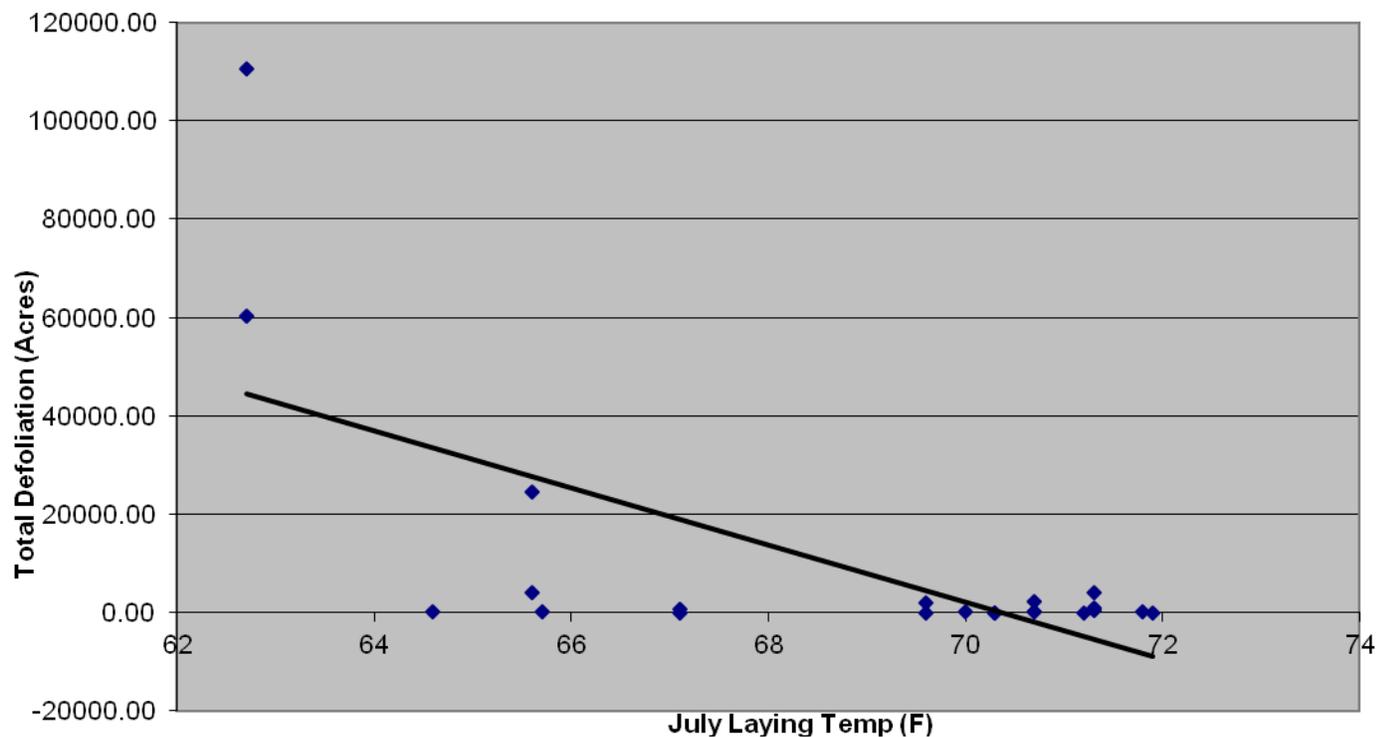
Figure 10. Shows total defoliation in acres vs. annual average temperature in degrees
Fahrenheit for the month of July, which coincides with gypsy moth egg laying. Temperature
was recorded with a year lag. The unusually high defoliation numbers are Marinette, Sauk,
and Columbia counties. P-value = .00075 R squared = .44

Discussion:

The first part of my hypothesis is that there is a correlation between the amount of
defoliation and the climate factors of annual average wind speed, total equivalent
precipitation, and annual average temperature. Another part of my hypothesis is that when
wind speed and average temperature increase the gypsy moth's activity also increases. The
last element of my hypothesis has to do with larvae activity in gypsy moths and the
correlation between it and precipitation, namely that increased precipitation results in
decreased larvae activity. The results of my data in figures 5, 6, and 7 show that weather
and gypsy moth defoliation are not correlated in the 10 counties that I studied. With P-
values at above .5 the results of my study are not dependent to each other. The figures 5, 6,

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and 7 that are shown here are skewed to the left, which show a trend of decreasing defoliation as temperature increases. Figures 8, 9, and 10 are analyzing temperature on specific months April and July as well as determining if time lag plays a role in defoliation numbers. The p-value of temp-1 and the month of July laying temperature were below .05 which makes me believe there is a correlation with defoliation. The results of my experiment show me that there is a correlation between temperature and defoliation. Figures 8 and 10 show defoliation decreasing as temperature increases. This is opposite of what I hypothesized for temperature. The interesting thing about Wisconsin in terms of my study is that it is on the edge of the gypsy moth expansion line. This allows me to look at things as they are unfolding.

Other variables that could have an effect on gypsy moth defoliation that I would look at in a future study are the treatment methods that are used across the USA to help manage the gypsy moth. I feel that if the data can be found and collected there is room for improvement in the management effort. Management of the gypsy moth can improve by looking at the climatic factors shown to favor an increase in population. Knowing what factors could trigger defoliation events can make it easier for states to effectively manage gypsy moths. Furthermore, taking the data in GIS can open more doors to the efficiency of control methods. These control methods are the future of gypsy moth control and are important enough to warrant future study. Treatment methods are an important variable that I didn't have access to in my study due to lack of data. Possessing this data would allow me to see how various treatments affect the amount of defoliation or how climate plays a role in determining the effectiveness of a certain treatment method. A future study would take into account all of the factors that I used as well as variables like treatment methods and trap counts. All of these variables need to be compiled and tested which will lead to an increase in understanding of the gypsy moth and better ways to prevent damaging defoliation.

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