HESSIAN FLY SEASONAL FLIGHT ACTIVITY IN OKLAHOMA’S WHEAT GROWING REGIONS

By

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HESSIAN FLY SEASONAL FLIGHT ACTIVITY IN OKLAHOMA'S WHEAT GROWING REGIONS

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Abstract: Wheat is the most economically important food crop grown in Oklahoma. The Hessian fly is a common pest in wheat in all of the wheat production zones of North America. The Hessian fly was first recorded coming into the United States in the 18th century and Hessian mercenaries were blamed for the introduction as they may have brought the insect over in their straw bedding materials. Their introduction, however, can be linked to numerous introductions at multiple locations within the United States. When Hessian fly populations within a field exceed approximately 1 per tiller, the infestation is considered damaging and above the economic injury level. Such Infestations warrant the use of population control measures. The most effective way of controlling Hessian fly populations is through the sowing of resistant wheat cultivars. Insecticides, late-planting, and crop rotation are included in the Hessian fly control measures amongst other methods. Little is known about the flight patterns of Hessian fly over time in Oklahoma's wheat growing regions. A state wide survey was conducted attempting to characterize seasonal flight patterns of the Hessian fly in Oklahoma. Another objective of this research was to correlate observed flight activity with statewide weather patterns. Understanding the yearly trends in flight patterns could allow producers to better time their use of control measures. Sticky traps accompanied with PheroNet® (PheroNet, Alnarp, Sweden) Hessian fly pheromone lures were placed in wheat fields and pastures statewide and sampled year round for two growing seasons (2011/2012 and 2012/13). The numbers of Hessian fly per trap were recorded and compared with weather patterns such as precipitation and temperature. There were two discrete flight episodes observed during both growing seasons that were flanked by periods void of observable flight. One small fall flight period and one prolonged spring flight period were recorded and there was no flight observed at most locations during the extreme summer or winter months. These findings can help Oklahoma wheat producers correctly time Hessian fly control measures to coincide with the most effective periods when Hessian fly are susceptible to control methods.

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CHAPTER I

INTRODUCTION

With an average of about 5 million acres planted annually, wheat is the most important food crop grown in Oklahoma (NASS 2014). It is grown for 3 purposes: forage only, grain only and the forage and grain dual-purpose system (Krenzer 1994, Hossain et al. 2004). The Hessian fly is a major pest in winter wheat and is present in damaging numbers in all of the United States' wheat growing regions (Holtzer 2006). Hessian fly was first discovered in North America on Long Island, New York in 1779. Hessian mercenaries were blamed for the introduction; it is thought that the flies were ushered overseas in their straw bedding (Ratcliffe and Hatchett 1997). Recent findings suggest that the pest was introduced to North America at multiple locations and on multiple occasions (Morton and Schemerhorn 2013, Johnson et al. 2004). Although it is not known when the Hessian fly entered Oklahoma, it was documented in the Southern Great Plains in Kansas in 1871 (Salmon et al. 1953), it is assumed that flies entered Oklahoma at a similar time.

Hessian fly damage wheat throughout the growing season, by limiting the potential grain production: causing plant lodging/ stem breakage, preventing the grain head from filling, and killing or stunting individual tillers (McColloch 1923, Hill et al. 1943, Buntin 1999, Flanders et al. 2013). The economic injury level for the Hessian fly is approximately 1 larva or pupa per tiller (Alvey 2009) and the production of wheat for forage and grain is adversely effected when the infestation intensity exceeds approximately 10% of total tillers (Buntin 1999).

Hessian flies have been shown to cause economic loss to wheat when infestations exceed an average of 1 larva or pupa per tiller (Alvey 2009). In recent years, damaging Hessian fly infestations have occurred in multiple areas in the wheat growing regions of the Southern Great Plains including Oklahoma and Texas (Holtzer 2006, Smith 2007, Royer 2005, Chen 2009). It is thought that this recent increase in Hessian fly damage is correlated with a combination of widespread planting of susceptible cultivars and a statewide increase in no-till wheat acreage (Alvey 2009, Holtzer 2006). Hessian fly population dynamics are likely complex, and subsequently, management in this region has focused solely on strategic deployment of resistant cultivars: this approach has been very effective at reducing local fly infestations (Royer and Giles 2011). Despite a long history of infestations in the Southern Plains, little is known about the biology of Hessian fly in this region.

Basic information on temporal activity could be useful for developing a more comprehensive pest management program. There is little known about the seasonal flight activity of Hessian fly in the Great Plains. There are many contributing factors for this lack of knowledge which include inefficient sampling techniques, difficulties with predicting the behavior of local populations and their activity, as well as predicting presence and abundance of subsequent egg and larval populations. Understanding the trends in flight patterns over time could be extremely beneficial to producers who want to know if Hessian flies are active in their farming system, or for producers who are attempting to time insecticide applications with Hessian fly movement and egg laying. The main goal of this research inquiry is to define predictable adult Hessian fly flight activity periods in Oklahoma.

Objectives:

I. Document adult Hessian fly *Mayetiola destructor* flight over time in Oklahoma's wheat growing regions.

II. Describe the relationships between *M. destructor* flight activity and weather patterns.

CHAPTER II

REVIEW OF LITERATURE

Wheat Production

Annually in Oklahoma there are approximately 5 million acres of hard red winter wheat planted for 3 purposes: grain; livestock forage; and/or forage plus grain production (Krenzer 1994, Flanders et al. 2013, Hossain et al. 2004, Johnson et al. 2004, NASS 2014). These diverse uses for wheat in Oklahoma are a result of unique interactions between average environmental conditions and wheat biology found in the Southern Great Plains. Wheat can be a highly valuable forage crop and grazed during the late fall, winter and early spring in Oklahoma, and if cattle are removed prior to formation of the first hollow stem in spring, the crop will yield grain in this dual purpose system.

Increases in fuel prices and concerns over water availability have driven a number of Oklahoma wheat producers in recent years to establish no-till production systems (Royer 2005). This practice saves on fuel costs by reducing tillage while increasing moisture retention, reducing erosion, increasing soil nutrition (carbon sequestration) and decreasing soil compaction (Lara 2006). These practices do promote weed infestations particularly volunteer wheat, and require timely herbicide applications if wheat is to be grown successfully (Edwards et al. 2007). In addition, no-till systems increase the amount of crop residue and support insect pests such as Hessian fly which can over-winter/summer in this residue (Chen et al. 2009). Indeed, the recent increase in no-till wheat acreage is correlated with a corresponding increase in virulent Hessian fly infestations throughout the Southern Great Plains (Chen 2009, Alvey 2009).

Common Insect Pests of Wheat

Several common herbivorous insects attack wheat throughout the Southern Plains (Royer et al. 1998) and the most important are found within the Aphididae: greenbug (*Schizaphis graminum*), rice-root aphid (*Rhopalosiphum rufiabdominalis*), bird-cherry oat aphid (*Rhopalosiphum padi*), Russian wheat aphid (*Diuraphis noxia*), and English grain aphid (*Sitobion avenae*) (Mullins 2008). Cutworms (*Agrotis spp.* and *Euxoa auxilaris* Grote) are occasionally found feeding on wheat, but most other pests are highly sporadic and include white grubs (*Phylophaga* spp. and *Cyclocephala* spp.), armyworms (*Spodoptera frugiperda* (J. E. Smith), as well as *Pseudaletia unipuncta* (Haywoth), and a few mites (*Pentalius major*, *Aceria tosiochella*, and *Petrobia Lateens*).

The Hessian fly (*Cecidomyiidae: Mayetiola destructor*) is traditionally one of the most economically damaging pests in the winter wheat systems of North America (Holtzer 2006) and has re-emerged as a significant pest during the past decade (Alvey 2009, Chen et al. 2009). It is thought that recent severe infestations of Hessian fly in this region have occurred because of the emergence of virulent biotypes, the widespread planting of susceptible cultivars, and an increase in no-till wheat systems that provide refuge for pupae (Chen 2009, Alvey 2009).

Hessian Fly History and Recent Outbreaks

It is thought that the Hessian fly evolved in the regions of the world that gave rise to modern wheat; southwest Asia and the southern Caucasuses (Ratcliffe and Hatchett 1997). The first US infestations of Hessian fly were reported on Long Island, NY in 1779. It is thought that flies were first introduced to the New World via the straw bedding of Hessian Mercenaries (Ratcliff and Hatchet 1997). However, more recent investigations have determined that the fly was likely introduced on multiple occasions and from multiple locations (Morton and Schemerhorn 2013, Johnson et al. 2004). There is no documented publication of the Hessian fly's arrival in Oklahoma, but flies were discovered in Kansas in the 1880's and in Texas in 1878 thus are likely to have established in Oklahoma at a similar time (Packard 1883, Schuster and Lidell 1990, Salmon et al. 1953).

The Hessian fly has been a common pest across the United States since its introduction, and infestations have been sporadically severe during the past few decades across the wheat growing regions of the Central and Southern Plains (Hatchet et al. 1981, Smith 2007). During the 1978 growing season, Hessian fly infestations were discovered along the Oklahoma-Kansas border, but damage was not reported as being widespread until 1984 when a severe infestation in Texas caused more that $5 million in damage. In 1993, infestations in Kansas caused yield losses of 6-30% (Holtzer 2006). During the 2005/2006 and 2006/2007 growing seasons, localized severe infestations (>10 flies / wheat tiller) in North East Texas and Oklahoma resulted in up to 75% yield losses (Smith 2007, Alvey 2009, Chen et al. 2009). During this latest outbreak in Texas and Oklahoma it was noted that Hessian fly populations occurred mostly at sub-economic levels throughout the major wheat growing counties in the region, but many of the highly infested fields were continuously “no-till” fields or fields in close proximity to infested no-till fields (Hodges et al. 2007, Alvey 2009).

Hessian Fly Description and Biology

Adult Hessian flies are relatively small gall forming midges with morphological characteristics similar to those of mosquitos in size and shape. It is commonly thought that adult emergence occurs in the fall months after wheat has been sown as well as in the spring when average temperatures warm again (Johnson 2004). During a relatively short adult lifespan of only one to two days, female Hessian flies must successfully mate and locate wheat tillers on which to lay their eggs. The small orange eggs hatch in three to ten days depending on temperature (Flanders et al. 2013). Young larvae move along the leaf surface and develop in the crown or node. Larvae resemble white grains of rice and are found between the leaves and the stem or culm of the wheat plant throughout development and during the pupal stage. The larvae feed on sap for a maximum of 30 days, but the third and final instar, often termed a prepupal stage, does not exhibit any feeding behavior (Gagne and Hatchett 1989, Wellso 1991). The insect no longer feeds after the development of the puparial case. Adults will emerge from puparia when environmental conditions are suitable; however they can remain in diapause in this stage during periods in which the temperature is below 40° F and aestivate when temperatures are above 80° F (Flanders et al. 2013). Puparia can remain in diapause for periods up to 3.5 years (Wellso 1991, McColloch 1923). The puparia are commonly known as "flaxseeds" because of their likeness to the shiny brown seed. The Hessian fly can complete a whole life cycle in 35 days under optimum environmental conditions (Flanders et al. 2013). Because Hessian fly adults are weak fliers, infestations are thought to occur locally provided the habitat is conducive for survivorship and susceptible cultivars are planted regularly. Indeed, Buntin et al. (1999) documented a correlation between the number of infested tillers in the fall and the number of infested tillers in the spring, which indicates that fly infestations are primarily local.

Biotype is a term used to describe variability within a species, particularly for crop pests with the ability to feed on host plants and/or vector pathogens (Diehl and Bush 1984, Eastop 1973, Russell 1978). Differences in physiological traits can vary dramatically among biotypes within a species, and for the Hessian fly, biotypes are based on the ability of populations to overcome identified wheat resistance genes (Chen et al. 2009). A wheat cultivar is considered resistant when greater than 80% of plants tested show high levels of resistance. Resistant cultivars have what are known as resistant genes that essentially eliminate the effectiveness of Hessian fly larval feeding secretions rendering them unable to feed. Wheat plants that exhibit no signs of feeding or damage are considered resistant (Chen et al. 2009). Currently, there are 16 known Hessian fly biotypes but the "Great Plains" biotype is commonly found throughout the Southern Plains wheat growing regions (Royer 2005, Chen et al. 2009).

Hessian Fly Injury and Damage

The precise method Hessian fly larvae use to feed on wheat is not clearly understood. The mouthparts of the first instar are pointed and presumably adapted to pierce plant tissues. The larval tooth contains a long-grooved hole that is assumed to deposit larval salivary secretions into the host (Hatchett et al. 1990). One hypothesis is that these secretions cause physiological changes in the plant cell walls rendering them more permeable (Shukle et al. 1985, Hatchett et al. 1990). Wheat plants infested with Hessian fly are often stunted and have a characteristic blue green tinge. If the infestation is severe enough, the plants will be lodged or killed by larval feeding. In a heavily infested field, each plant will have some tillers stunted or killed by larval feeding and some tillers void of larvae that exhibit no obvious symptoms.

Hessian fly limit the maximum productivity of wheat plants by killing or stunting vegetative growth, preventing grain head development, and breaking or bending the stem causing the plant to lodge (McColloch 1923, Hill et al. 1943, Buntin 1999, Flanders et al. 2013). If a severe enough infestation occurs during a vulnerable growth stage, damage from Hessian fly feeding can be widespread. In the fall, as young plants are emerging from the soil, Hessian fly infestations can be severely damaging and reduce yields to near zero. Severe spring infestations can cause considerable yield loss via the lodging and dwarfing of the plants. The quality of the grain can also be detrimentally affected. Severely infested fields are often confused for fields exhibiting heavy hail damage (Flanders et al. 2013).

Hessian fly significantly reduce every component of wheat yield including: seeds per spike, seed weight, spikelets per spike, spikelet weight and seeds per spikelet. As verified by Estes et al. (1985) and Buntin et al. (1999), when 5-8% of tillers are infested there is a measurable reduction in grain yield. According to Buntin et al (1999), Hessian fly infestations of 2 larvae per tiller reduce the average grain weight by 41.3%. This study also demonstrated that an infestation occurring during the grain head filling stage results in a linear loss of mean weight; during the fall, each increased percentage point of larvae per stem caused a 21.1 kg/ha loss whereas each percentage point increase caused a 12.8 kg/ ha loss during the spring. Alvey 2009 demonstrated a significant negative relationship between wheat yield and average Hessian fly intensity; for every fly immature per tiller over an entire growing season 386 kg/ha (≈5bu/acre) of wheat yield is lost. The amount of sustained injury that would warrant the cost of control methods is known as the economic injury level or EIL (Stern et al. 1959). This is a useful threshold that allows the producer to assess the intensity of an infestation and subsequently make an informed decision regarding the application of a control measure. According to Alvey (2009), an average of one Hessian fly per tiller (causing ≈5bu/acre of loss) justifies preventative or curative control efforts.

Management

There are multiple techniques that can be utilized to prevent damage from Hessian fly populations within a wheat system. These strategies are based on an effort to prevent feeding by larvae as this is the only life stage of the Hessian fly that causes injury and damage to wheat (Buntin 1999).

Planting Date. One commonly used cultural control method for Hessian fly is the adherence to "fly-free" planting dates. This technique is also referred to as delayed planting (Flanders et al. 2013). In northern wheat production regions of the US, it is thought that planting wheat after the first freeze reduces the fly's ability to infest a wheat crop during the fall and subsequently the potential to cause damage because freezing temperatures prevent Hessian fly growth and emergence. As would be expected, this method has been more effective in the northernmost wheat growing regions of the US compared with the southernmost regions where mild winters do little to deter growth and development of the Hessian fly (Flanders et al. 2013). Often an adequate freeze might not occur until well into December in these southern areas. Buntin (1992) found that if a producer planted at the recommended date prescribed for the southeastern US, the risk for a severe Hessian fly infestation increased. Because of mild winters, fly free dates do not work consistently in Kansas, and have not been observed to work in Oklahoma and Texas (Patrick and Knutson 2006, Knodel 2008, Whitworth 2005, Alvey 2009).

Crop Rotation and Spatial Proximity. The planting of other winter crops which do not support Hessian fly growth and reproduction can be an effective prevention measure (Flanders et al. 2013). Severe Hessian fly infestations may occur when wheat is planted near the stubble of the previous season's harvest crop; this stubble serves as a reservoir for over wintering/ summering Hessian fly populations (Flanders et al. 2013). Any method of rotating crops and effective weed control among fields can reduce the amount of wheat stubble and volunteer wheat thus effectively decreasing the size of the pest reservoir. The removal/burying of infested stubble are likely to reduce the chances of infestations (Flanders et al. 2013).

Because Hessian flies can diapause/aestivate in wheat stubble, planting on or near no-till fields may increase the likelihood of future infestations and can result in successively greater fly populations (Flanders et al. 2013). Because Hessian flies are weak fliers, their proximity to suitable plants in newly sown fields is a concern, and producers are recommended to plant susceptible wheat cultivars in fields as far from infested wheat stubble as possible (Flanders et al. 2013). Interestingly, Buntin (1999) documented that susceptible cultivars planted in the presence of or adjacent to cultivars that are resistant to Hessian fly are more likely to accrue infestations. Because volunteer wheat germinates early in the growing season, it is often the target of early emerging flies and thus is likely the start of new infestations. Controlling volunteer wheat in the landscape is also an important preemptive measure that allows producers to evade early fall infestations.

Resistance. Currently the most effective known strategy to avoid damage from Hessian fly populations is the practice of planting resistant cultivars (Buntin 1999, Chen et al. 2009, Royer and Giles 2011). Fields with heavy infestations where resistant cultivars were grown offer improved economic return margins compared to susceptible cultivars not treated with insecticide (Buntin et al. 1992). Several commercially available wheat cultivars that exhibit Hessian fly resistance have been strategically deployed against virulent biotypes throughout the US (Flanders et al. 2013). In Oklahoma, several recommended cultivars are resistant to the "great plains" biotype, but the most widely planted resistant cultivar is 'Duster' (Hunger et al. 2013). This cultivar was developed and released by Oklahoma State University in 2006 and was the most frequently planted cultivar during the 2012/2013 growing season (NASS 2013). According to Royer and Giles (2011), strategic planting of 'Duster' in areas with heavy fly infestations has significantly reduced damage caused by this pest.

Insecticides. Both foliar insecticides as well as neonicitinoid seed treatments are effective at controlling fall populations of Hessian fly. Systemic insecticides applied to wheat seeds such as Gaucho® (imadacloprid) and Cruiser® (neonicotinoid) are used to prevent damage in fields that have a history of severe infestations (Van Duyn et al. 2004). When populations are high and flight patterns are predictable, foliar insecticides can be used to kill adults and hatching larvae if timed correctly (Flanders et al. 2013). Warrior®, Mustang Max™ and Fury™ are examples of foliar pyrethroid insecticides that have been reported to be efficient killers of adult Hessian flies (Van Duyn et al. 2004). Hessian fly infestations have been targeted for control by the application of foliar insecticides within furrows prior to sowing, but widely broadcast insecticides have little to no impact on damage once an infestation has already been established (Buntin 1990, Buntin 1999, Chapin et al. 1991).

Foliar treatments can be referred to as a sort of rescue treatment that may prevent damage and thus are economical, but only on susceptible wheat cultivars and in heavily infested areas (Flanders et al. 2013). Van Duyn et al. (2004) reported that prior to the use of foliar insecticides, three of five criteria must be met: Hessian fly infestations have caused severe crop damage in adjacent areas in previous years with eggs apparent on the leaf's surface, wheat was sown on the same field as the previous year's wheat crop, wheat was planted adjacent to the previous year's field, seeds that were sown were not coated with a systemic insecticide, a resistant cultivar is not sown and/or this year's crop was planted adjacent to or on the same field used for the previous year's crop. The use of foliar insecticides is rare in the Southern Plains, but in the Southeastern US, a preventative pesticide application is regularly recommended during the spring (Buntin 1999).

The essential oils of several plants native to Morocco have been found to exhibit insecticidal properties against the Hessian fly. *Mentha pulegium* and *Origanum compactum* were found to be considerably toxic to adults whereas *Ammi-visaga, Pistacia lentiscus, M. pulegium*, and *O. compactum* were found to be most efficient at killing Hessian fly eggs. Of these, the most effective at killing both adults and eggs was *Mentha pulegium* (Lamiri et al. 2001). Essential oil effectiveness has not been evaluated against Hessian fly populations in the Southern Plains.

Biological Control. Parasitoids reduce Hessian fly survivorship, however, the impact on population dynamics have not been studied. According to Gahan (1933) there are at least 41 species of chalcidoid and proctotrupoid parasitoid wasps from Europe and North America that serve as natural enemies of the Hessian fly. The relative abundance and distribution of these parasitoids varies dramatically among climatic and geographical zones (Schuster and Lidell 1990). Previous studies in Northern Idaho, Washington, New Zealand and North Texas have found Hymenopteran parasitoids to be effective at killing Hessian fly eggs, larvae or pupae (Bullock et al. 2004, Pike et al. 1983, Prestidge 1992, Schuster and Lidell 1990,). In Texas, *Homopourus destructor* (Say) (Hymenoptera: Pteromalidae), *Eupelmus allynii* (French) (Hymenoptera: Eupelmidae) and *Trichomalopsis subapterus* (Forbes) (Hymenoptera: Pteromalidae) were all observed emerging from Hessian fly larvae and pupae but only during the spring months (Schuster and Lidell 1990). *Platygaster hiemalis* (Forbes) (Hymenoptera: Platygastridae), *Pediobius epigonus* (Walker) (Hymenoptera: Eulophidae) and *Eupelmus vesicularus* (Retzius) (Hymentoptera: Eupelmidae) were all found in Idaho but not Texas, Washington, or New Zealand (Bullock et al. 2004). *Homoporous destructor* was labeled as an important natural control agent of the Hessian fly in Idaho, Texas, and Washington (Schuster and Lidell 1990, Bullock et al. 2004, Pike et. al. 1983). Currently, little is known about what species of Hessian fly parasitoids are common in Oklahoma, or the level of parasitism that occurs among the wheat growing regions of the state.

CHAPTER III

MATERIALS AND METHODS

Pheromone Trapping of Hessian Fly Males

Trap Deployment. Trece Phercocon VI® delta traps were loaded with their accompanying sticky cards and baited with PheroNet® (PheroNet, Alnarp, Sweden) Hessian fly pheromone lures. Pheromone components were contained within and emitted from a 9mm rubber septa dispenser insert mounted on a 750 x 250 mm cardboard card. The pheromone lures contained components of the female Hessian fly calling pheromone that best attracted Hessian fly males in prior studies (Anderson et al. 2009). Dispersers contained the following mixture: (2S, 10E)-I O-tridecen-2-yl acetate (2S-E10-13:OAc), (2S,8E,10E)-8, 10-tridecadien-2-yl acetate (2S-Z8-E10-13:OAc), 10- tridecadien-2-yl acetate (2S-E8-E10-13:OAc), (2S)-tridecan-2-yl acetate (2S-13:OAc), (2S,10E)-10-tridecen-2-ol (2S-E10-13OH), and/or (2S,8Z,10E)-8. Pheromone lures were fastened to the top of the cage.

Delta traps with labeled baited sticky cards (location/date) were mounted on ~1m metal stakes (See Figure 3) attached with metal wire at canopy level throughout the growing season. Anderson et al. (2012) confirmed that pheromone baited sticky cards result in the most adult Hessian fly captures when placed at canopy level, therefore as wheat matured throughout the growing season, the height of sticky cards was adjusted to match the height of the canopy. Traps were placed near the center and on the periphery of designated fields. During the growing seasons of 2011/12 and 2012/13 at each location/field, baited sticky cards were exchanged approximately every 10 days during the growing season and new baited sticky cards were replaced inside the delta cages. Sampling dates varied because of heavy precipitation events, road closings, and pesticide applications.

Baited sticky cards were removed and transported to the laboratory and stored in a freezer at -5°C prior to counting Hessian fly adults and deployment/removal dates were logged. Hessian flies on sticky cards were identified using a Leica S8 APO 80x stereomicroscope (See Figure 4). Flies were identified to the species level using morphological taxonomic keys (McAlpine 1981) and compared with specimens on record at the K. C. Emerson Entomology museum at Oklahoma State University. In addition, a sample of Hessian fly adults on sticky cards was sent to Dr. Ming Chen at Kansas State University and confirmed as Hessian fly using PCR markers (Chen et al. 2014). The total number of Hessian flies per trap were summarized by location and date of collection. All data was entered and maintained using Excel 2013 for Windows 7 (Microsoft Corporation 2013).

Sample Locations.

Locations were chosen in an attempt to represent the wheat growing regions of Oklahoma. During the 2011/2012 growing season, traps were deployed at 20 locations near: Perkins, Marland, Blackwell, Woodward, and El Reno Oklahoma. During the 2012/2013 growing season, traps were deployed at 17 locations and included sites near Altus and Cashion Oklahoma. Each site was characterized as either grazed, conventionally tilled, no-till, primarily grass pasture, and/or as a variety grain trial. No-till wheat fields were identified by the presence of wheat stubble left over from the previous growing season. Grazed fields were those with cattle feeding on them throughout most of the growing season. Those areas designated pastures were mostly covered with native flora. Those labeled as variety grain trials consisted of a grid of small experimental plots in which numerous wheat varieties are grown together.

Degree Day Calculations

Physiological degree day accumulations for the Hessian fly were calculated using the DEGDAY.xls program provided online by Snyder (2005). The program uses parameters for the calculation of degree days based on the methods developed by Zalom et al. (1983). Based on the values of the high and low developmental thresholds entered into the program for Hessian fly physiological growth, the program performs the single triangle as well as the single sine wave degree day calculations for estimating degree days (Higley et al. 1986). The single sine wave function of the DEGDAY.xls program assumes that daily fluctuations in temperature are cyclical and take the shape of a sine wave in which the morning low temperature isn't necessarily equal to the evening low temperature (Allen 1976, Zalom et al. 1983). Thus the sine-wave and the "single triangle method" more accurately portray the daily temperature fluctuations than does a simpler averaging method which assumes the morning and evening minimum temperatures to be equal in value (Roltch et al. 1999). The single sine value was used for this study in accordance with previous Hessian fly research on generational timing (Buntin 1990, Prestidge 1992).

Each location with Hessian fly males captured during the fall was used to calculate degree day accumulation. Alvey (2009) observed at least two Hessian fly generations (fall and spring) on winter wheat in Oklahoma. Therefore, the last date that a capture was observed during the fall was used as the "biofix" point in an effort to predict the occurrence of the spring/second generation. For each location with a fall capture, the number of heat units between the last male captured in fall and the first captured in the spring were calculated using the single-sine method. The Hessian fly estimated lower and upper developmental thresholds of 1.6°C and 26.7°C were used in DEGDAY program calculations (Foster and Taylor 1975). Mean degree day accumulation was calculated for each growing season and for both years combined.

Daily temperature and precipitation values were obtained from Oklahoma's Mesonet meteorological database (Mesonet 2011, Mesonet 2012 and Mesonet 2013). The closest Mesonet station to each of the sampling locations was used to calculate degree day accumulation for each trapping site.

CHAPTER IV

RESULTS

2011/2012 Growing Season

Flight Activity: 2011/2012 Growing Season

Captures of Hessian fly males during the 2011/2012 growing season revealed a relatively clear bimodal distribution indicating the development of two generations (Figure 1). During late October 2011, relatively few to zero Hessian fly males were captured on sticky cards at sample sites near Blackwell, Marland, Perkins and Woodward Oklahoma (Figure 1), and there were no flies on traps at any location between mid-November to late-February. Spring flight of emerging males was first detected near Blackwell, Marland, El Reno and Perkins in late-February / early-March and observed at nearly every site by mid-April. Date of peak captures varied among sites (3/29/12-4/25/12) and ranged from 200 and 1794 flies per trap/period. The highest capture count occurred in a no-till wheat field near Marland; the sticky surface of one trap (collected on 4/25/12) was completely covered with 1794 male Hessian flies.

Flight Activity: 2012/13 Growing Season

Captures of Hessian fly males during the 2012/2013 growing season revealed late fall flight activity, but late spring captures varied considerably among dates within sites. A distinct spring flight pattern and clear second generation was not readily observable at these trapping sites (Figure 2). Indeed, at a few locations, captures of males during June 2013 indicate the presence of a third generation. During fall 2012, captures per trap/date were again relatively small (<18 males) at all locations, but activity extended into December (Figure 2). Fall flight of male flies was first detected at sites near El Reno on 10/23/12 and at sites near Marland on 11/6/12, and was detected as late as 12/4/12. Between 12/9/12-3/6/13, no flies were captured at any location through the duration of the winter. The first spring capture of a male Hessian flies occurred on 3/15/13 at a sample location near Perkins in a conventionally tilled wheat field. Hessian flies were captured at all locations during spring 2013 by 3/25/13. Flight continued throughout the spring months rather inconsistently until 6/19/13 when all wheat had been harvested. Date of peak captures varied among sites and the highest capture count occurred in a conventionally tilled wheat field near Blackwell; the sticky surface of this trap (collected on 6/11/13) had less than 700 male Hessian flies.

Degree Day Accumulation Totals

Degree day (DD) accumulations were summed only at trap locations in which 1 or more male Hessian flies were caught during fall months. During the 2011/12 growing season, traps near Marland, Blackwell, Perkins and Woodward were used for degree day calculations (Table 1). The dates that the last fall flies were observed on sticky traps at all locations in 2011/12 ranged from 10/21/11-11/10/11, and the dates when spring flight resumed ranged from 2/24/12 near Marland to 4/13/12 near Woodward. The average accumulation of degree days between last fall flight and first spring flight for all locations was 933 DD, but accumulated degree days varied between 534 DD (Marland) and 1329 DD (Woodward).

During the 2012/13 growing season, traps near Marland, Blackwell, El Reno and Woodward were used for degree day calculations (Table 2). The dates that the last fall flies were observed on sticky traps at all locations in 2012/13 ranged from 10/23/12-12/4/12, and the dates when spring flight resumed were rather homogenous and ranged from 3/25/13-4/5/12. The average accumulation of degree days between last fall flight and first spring flight for all locations was 665 DD, but accumulated degree days varied between 439 DD (Blackwell) and 1021 DD (El Reno).

The average degree day units accumulated between last fall capture and first spring capture of male flies (all locations both years) was 800 DD (See Tables 1 and 2). Sixteen trap locations were used for degree day calculations over both years. Again, locations with any fall flight observed on sticky card and were used for this comprehensive degree day calculation. Of those, 6 were greater than 900 DD. Other studies examining Hessian fly development have excluded these large calculations because they may capture of a third generation. Excluding locations with >900 DD accumulation, an average of 631 DD was calculated for all locations both years.

Degree day accumulation was also calculated at Marland no-till trap #2 as there were apparently multiple discrete flight episodes during the spring of 2013 at that location. There was 836 degree days accumulated at this location between the dates of 4/5/13 and 6/2/13 which may represent an additional that spring.

TABLES

Table 1. Accumulation of Celsius degree days between last fall flight and first spring flight at 8 locations during the 2011/2012 winter wheat growing season in Oklahoma.

Table 1. Degree-day calculations for 2011/12

Location	2011/12
Marland NT 1	534
Marland NT 2	979
Blackwell CT 1	911
Blackwell CT 2	911
Perkins G 1	836
Perkins G 2	640
Woodward CT	1329
Woodward VT	1329

Degree-day accumulations were performed using single sine-wave formulas following Zalom et. al 1983

Mean degree day accumulations (±SE) for 2011/12 is 933 ± 94.5 °C Degree Days. Calculations based on lower and upper developmental thresholds of 1.6°C and 26.7°C.

Table 2. Accumulation of Celsius degree days between last fall flight and first spring flight at 8 locations during the 2012/2013 winter wheat growing season in Oklahoma.

Table 2. Degree-day calculations for 2012/13

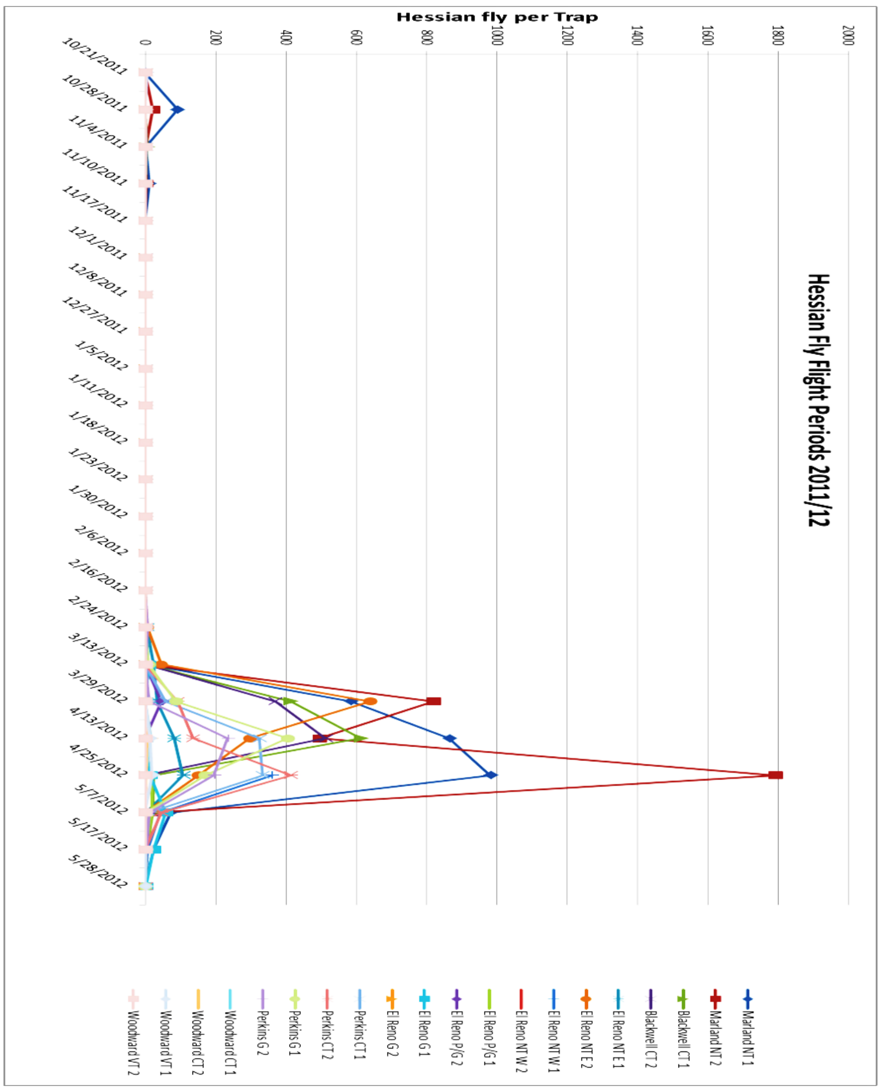
Location	2012/13
Marland NT 1	501
Marland NT 2	599
Marland NT 3	773
Blackwell CT 1	440
El Reno CT 1	667
El Reno CT 2	1021
El Reno NT 1	667
Woodward VT	654

Degree-day accumulations were performed using single sine-wave formulas following Zalom et. al 1983

Mean degree day accumulations (±SE) for 2012/13 is 665 ± 62.76°C Degree Days. Calculations based on lower and upper developmental thresholds of 1.6°C and 26.7°C.

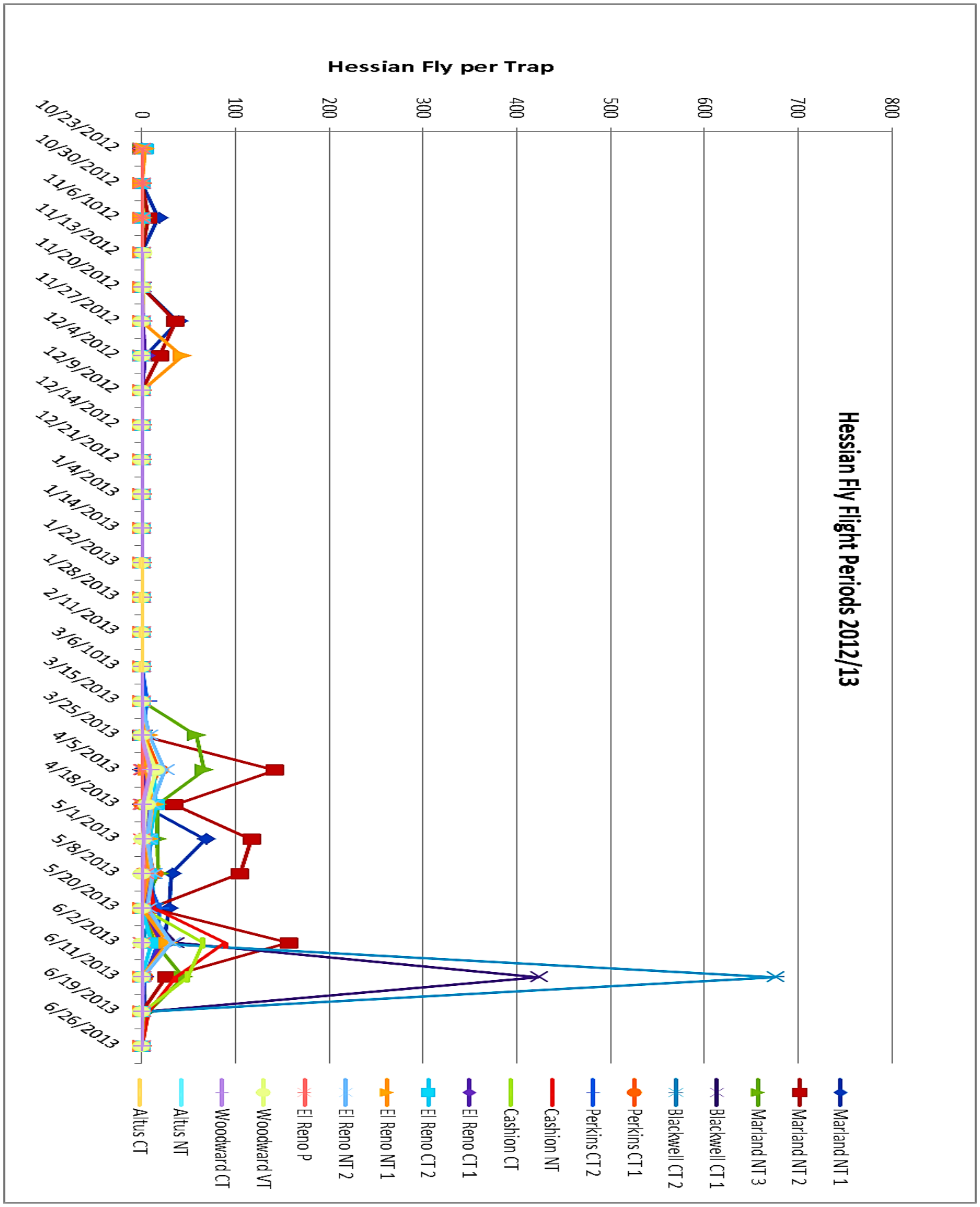
FIGURES

Figure 1. Total Hessian fly adult males on pheromone-baited sticky traps during the 2011/2012 winter wheat growing season in Oklahoma.



NT = No-till wheat, CT = Conventional tillage wheat, P = pasture, G = Grazed, VT = Variety Trial

Figure 2. Total Hessian fly adult males on pheromone-baited sticky traps during the 2012/2013 winter wheat growing season in Oklahoma.



NT = No-till wheat, CT = Conventional tillage wheat, P = pasture, G = Grazed, VT = Variety Trial

Figure 3. Trece Phercocon VI® delta traps loaded with sticky cards baited with PheroNet® (PheroNet, Alnarp, Sweden) Hessian fly pheromone lures.

Figure 4. A Hessian fly caught on a sticky card.

CHAPTER V

DISCUSSION

Because of the difficulty in sampling adult Hessian flies, little is known about flight patterns in the Southern Great Plains. The pheromone lures/traps used in this study have only recently been established as an effective sampling method to monitor Hessian fly seasonal activity (Anderson et al. 2009), and this approach was considered an efficient alternative method for describing the numbers of generations that can occur per year from distinct flight episodes (Wellso 1991). This approach represents an advancement over previous attempts to characterize the seasonal occurrence of Hessian fly because researchers can (1) avoid time-consuming dissecting of wheat tillers which targets established larval/pupal populations (Alvey 2009), and (2) utilize real-time flight activity to make pest-management decisions on insecticide applications that may reduce adult fly and hatching larval populations.

It is important to mention that only males were found on traps throughout the study because the blend of compounds used as a lure were components of the Hessian fly female's calling pheromone used exclusively to attract males (Foster and Harris 1991, Anderson 2009). Because of this, large portions of each emerging adult Hessian fly brood that are female likely went unnoticed. Hessian fly are also known to exhibit sexual biasing during emergence. Some broods will be mostly female whereas some will be mostly male (Schuster and Lidell 1990), and there could have been broods consisting mostly of females that also would not be observed for this reason.

Hessian Fly Flight Activity. During both growing seasons, the highest numbers of flies were caught in central and north-central Oklahoma. In 2011/12 the traps at locations in El Reno, Perkins, Marland and Blackwell all had greater than 200 flies per trap at some point during the spring sampling period. Similar regional trends were seen during the spring flight period of the 2012/13 growing season. The highest numbers of flies were caught on traps near Marland and Blackwell in north-central Oklahoma. Hatchett et al. 1981 found similar patterns with the highest densities of Hessian fly pupae found in northeast, central and south central Oklahoma. It is important to note that traps with counts approaching 1800 males are essentially fully covered and trapping efficiency must be reduced at higher densities because few additional captures could occur above that number. The highest number caught during a spring sample period (2012) was 1794 which was at a "no-till" location near Marland, but it is not known whether that trap count represented actual flight activity, or that male populations were much higher.

Interestingly, Hessian fly adults were caught at relatively low numbers during this study in Woodward County, a county that had no previous record of Hessian fly. Hatchett et al. (1981) sampled over a three year period from 1976-1978 and found no flies in the entire western 1/3 of Oklahoma suggesting that either the Hessian fly has spread westward since that time or that pheromone trapping improved detection.

Three wheat producers provided cultivar names for wheat fields sampled in Blackwell, Marland and El Reno in 2012/13. The susceptible cultivar 'Armor' was sown in the fields sampled near the city of Marland and as would be expected appeared to produce high numbers of Hessian fly at all locations. 'Billings' is considered susceptible to Hessian fly (Hunger 2013) and was planted at fields near Blackwell and some of the highest totals (n=675, n=423) of Hessian flies were caught on sticky cards at this location. The flight episodes detected during these high captures could have come from puparia within the field, however, very low numbers of Hessian fly larvae and pupae were detected in wheat tillers (Giles and Royer 2012). This finding suggests that the large flight episodes detected could have come from adjacent wheat fields or host reservoirs and highlights the ability of Hessian fly to enter a wheat field from surrounding areas despite their poor flight abilities relative to other insects. Alternatively, the pheromone traps either (1) may have been so effective at attracting males, females did not mate and laid eggs, or (2) there is no correlation between male trap captures and immature populations in nearby wheat. Clearly, the relationship between trap captures and population dynamics requires further investigation.

Also, relatively small numbers (between 1 and 32 flies/ trap) of Hessian fly were detected throughout the spring flight periods during 2012/13 in fields sown with the resistant variety 'Duster' near El Reno (Hunger 2013). Much larger numbers (n=639, n=360) of adults were detected in these and adjacent fields near El Reno when traps were deployed in fields with the susceptible cultivar 'Endurance' during 2011/12. Dissections of wheat plants were not performed in El Reno thus a link between the intensity of Hessian fly pupae/ larvae found in developing wheat and the adult flight episode detected at those locations cannot be inferred. Because 'Duster' is so effective at preventing Hessian fly feeding, resistance was likely a key factor in the extreme difference in the number of adult Hessian fly caught during the 2012/13 growing season.

Hessian fly are known to be able to survive and reproduce on 17 different genera of grasses in the Triticeae and the Bromeae tribes (McColloch 1923, Barnes 1956, Jones 1936, Harris et al. 2003). Pasture lands in Oklahoma can have many of these alternative host grasses including Canada wildrye *Elymus Canadensis* (L.), western wheatgrass, *Pascopyrum smithii* (Rydb.), and crested wheatgrass, *Agropyron cristatum* (L.) (Jones 1936). The highest trap captures occurred in no-till and conventionally tilled wheat sites as expected, but low numbers of Hessian fly males were captured during 2011/2012 at sites comprised primarily of native vegetation with no history of wheat. Flies collected from these sites may be infesting common suitable wild hosts and related alternative host grasses. With the large amount of pasture located in western Oklahoma, further investigation would be required to quantify the degree to which Hessian fly larvae and pupae may utilize alternative hosts.

Seasonal Flight Trends. Pheromone trapping data from this study clearly indicates that Hessian fly flights only occurred during autumn and spring in Oklahoma. No flight activity was observed throughout the extreme summer or during the winter months at any of the locations sampled. Because Hessian fly adults live only a maximum of about 3 days (Harris and Rose 1991), and the major flight episodes lasted longer than the lifespan of an adult Hessian fly, it can be inferred that there were multiple emergence episodes and subsequent oviposition periods during months where major flight periods occurred. During the growing seasons sampled, flight periods in Oklahoma lasted up to three months (especially year 2). During such periods when favorable conditions are present, multiple broods are likely to be emerging and mating with generational flight overlapping. It is assumed that during these periods, a sufficient amount of physiological degree days could accumulate allowing for the growth and emergence of multiple generations during spring.

As expected, compared with the fall flight periods, the spring flight period was more prolonged and had higher captures at most locations. During both seasons sampled, the spring flight period lasted approximately 3 months. During the fall, the longest period where flies were found during consecutive sample periods on the same trap was during the 2011/12 growing season in Marland where flies were recorded from 10/28/11-11/10/11. The spring flight period is prolonged because ambient temperatures more suitable for flight/emergence are present for an extended period of time and multiple spring generations may be overlapping (Harris and Rose 1991).

One major difference between the two growing seasons was the date at which spring flight ended. During the 2011/12 growing season, almost all flight had ceased by 5/17/12 whereas during the 2012/13 growing season spring flight ended at all locations more than a month later in the calendar year on 6/19/13. Wheat was harvested nearly a month later throughout Oklahoma during the 2012/13 growing season than during the 2011/12 season. Hessian fly flight during both seasons occurred only during months when wheat was present in fields. The relatively large numbers of flies caught in traps set during the spring months are indicative of the Hessian fly's population growth abilities (Anderson et al. 2012).

Number of Broods. Hessian fly emergence episodes are termed as broods rather than generations because not all individuals in a generation emerge in concert, rather they emerge in a stratified fashion over periods of weeks or years (Lidell and Schuster 1990). In the Northern and Midwestern wheat growing regions of the United States, Hessian fly are known to regularly have one autumn and one spring generation per growing season, but additional generations can occur under favorable environmental conditions (McColloch 1923). In the warm coastal plains regions of the Southeastern United States, up to 5 Hessian fly generations can occur each growing season making the Hessian fly a potential severe pest in this region (Buntin and Chapin 1990). Wellso (1991) summarized this continental trend stating that in the northern extremity of the Hessian fly's range there are on average two generations per year, whereas near their southernmost boundary there can be up to six generations per growing season. Essentially, the longer/warmer the growing season, the more potential there is for Hessian fly populations to grow rapidly and have produce additional generations (Barnes 1956, Morrill 1982, Bullock et al. 2004, Anderson et al. 2012, Wellso 1991). Indeed, in Southern Georgia, Hessian fly adults have been caught consistently throughout the growing season and during winter months, which indicates multiple generations in the southern extent of their North American range (Buntin 1999). It should be noted that discrete generations or broods might be difficult to identify as generational flight could certainly overlap over time.

Because Oklahoma resides at an intermediate latitude with respect to the North American landscape, we may therefore expect from two to six generations or broods per growing season based on average climate and growing conditions (Buntin 1990, Schuster and Lidell 1990, Buntin and Chapin 1990). As predicted from average climatic conditions, and based on flight activity, at least two generations of Hessian fly occur in Oklahoma. This flight data further confirms the findings of Alvey (2009) who documented a fall generation of immature flies and at least one spring generation.

While there appeared to be two flight “periods” during the two year study, some variation did occur among locations. During the 2012/13 growing season at traps near Marland there were possibly two discrete fall flight episodes and between two and three separate spring flight episodes. Degree day accumulations between the first and last of the obvious peaks was determined at the Marland trapping location during the spring and 836 °C DD elapsed in this period from 4/5/13-6/2/13. Thus at least two discrete generations could have developed, emerged and oviposited within that field during the spring of 2013. Traps at sites near Blackwell and El Reno had very similar catch rates during the same growing seasons with apparent multiple capture events for fall and spring. These discrete capture events represent delayed adult emergence, multiple generations, or both.

Flight Patterns and Weather. *2011/12.* The summer preceding the first growing season sampled was the state’s second driest on record since 1921 (Mesonet 2011). Fall flight during the 2011/12 growing season began in late October and early November at locations in Blackwell, Marland, Perkins and Woodward and ceased at all locations by mid-November. The entire state of Oklahoma was under severe drought conditions throughout 2011 and continued into mid-spring 2012 (Mesonet 2012). However, spring flight began during severely dry conditions at locations near Perkins, Blackwell and El Reno in late-February 2012 and had begun at all locations except Woodward by the end of March. It is commonly thought that a large precipitation event following a drought will prompt the emergence of Hessian fly adults (Packard 1928, Flanders et al. 2013) however spring captures occurred despite the absence of any appreciable rainfall events. March 2012 was the warmest March on record and was the 6th wettest month on record (Mesonet 2012). By April and May, extremely warm and dry conditions returned to the state and spring flight ceased at all locations by 5/28/12 which closely coincided with the maturation and harvest of the wheat statewide in 2012. .

2012/13. 2012 was the warmest year on record in Oklahoma and June-August 2012 was the 11th warmest such period recorded with a statewide average of 82.2 °F. Initial flight activity was detected during a mild fall by late-October and into early-November. Interestingly, a discrete second fall flight period was observed in Marland and El Reno between 11/27/12 and 12/4/12 well after the average first autumnal freeze for the state of Oklahoma. Cleary, and as has been suggested, fly-free planting dates may be of limited value in Oklahoma if fields are susceptible to invasion by Hessian fly as late as December. Oklahoma exists at an intermediate location between northern and southern latitudes and during extremely mild winters, conditions would be suitable for Hessian fly emergence, egg laying and development. However, during this study flight activity was not detected after December 4 indicating that conditions were too extreme for the production of a winter generation.

February, which is often the driest month in Oklahoma, was the 13th wettest in recorded history and was cooler than normal and Hessian flies were not captured until late-March 2013 in Blackwell, El Reno, Marland and Perkins. March was a relatively dry period further exacerbating the drought conditions but the lack of rain did not prevent emergence and flight activity of Hessian fly males. By late April, spring storms had polarized drought conditions statewide as the western half of the state was still considered to be under severe drought conditions and the Eastern half of the state saw significant precipitation. These conditions continued into June 2013 with a Mesonet site near Hooker recorded 0.08 total inches in May whereas Oklahoma County in Central Oklahoma saw its wettest May on record with 14.52 inches recorded (Mesonet 2013). All locations sampled were considered to be in the Eastern two-thirds of Oklahoma with the exceptions of Altus and Woodward. As expected, wet conditions at the eastern sites appeared to be linked to adult emergence and extended periods of flight activity/captures. Surprisingly, Hessian flies were captured during severe drought conditions in Woodward and Altus, but captures were low, and only for brief periods of time.

Schuster and Lidell (1990) found that in north-central Texas, all damaging Hessian fly infestations were present east of the 76 cm average annual precipitation line. In Oklahoma, sub-economic populations of Hessian fly larvae and pupae have been found in Custer and Washita counties both of which are west of the average annual 76cm precipitation (Alvey 2009). During both growing seasons sampled for this thesis, traps near Woodward Oklahoma caught small numbers of flies under extreme drought conditions. Despite the fact that damaging populations of Hessian fly are not often present west of the 76cm precipitation isocline in the Southern Great Plains (Schuster and Lidell 1990) there were still small flight periods of Hessian fly as far west as Woodward County Oklahoma, regardless of the presence of drought conditions. Thus, it initially appears as though the occurrence of considerable precipitation episodes are less important than other environmental factors such as temperature when determining the timing of emergence of Hessian fly adults from their pupal cases. Schuster and Lidell (1990) concluded that the accumulation of physiological degree day units might work in tandem with precipitation to predict emergence of a brood.

Degree Day Calculations. Because wheat develops throughout the winter in Oklahoma, it is reasonable to assume that the flies caught in a particular location during the fall may oviposit in the most easily accessible hosts during spring (Buntin et al. 1999). Therefore the date on which the last Hessian flies were caught during the fall was used as the biofix point for all physiological degree day (DD) accumulation calculations to predict the date the first flight during spring. With the exception of continuous no-tillage susceptible wheat landscapes, it is difficult to identify exactly where Hessian fly are eclosing from during the fall, and subsequently there is difficulty predicting fall flight based on spring captures. The discontinuous nature of available host plants during summer in Oklahoma often creates a temporal and spatial separation between spring and fall broods.

Similar studies have utilized the accumulation of degree day units in an attempt to predict flight activity periods of the Hessian fly in New Zealand as well as in the US state of Georgia. In

Georgia, even with regular rainfall events, the average number of degree day units calculated between broods of Hessian fly was extreme and ranged from 416 to 1,244 degree days (Buntin and Chapin 1990). For practical management purposes, these authors excluded the 5 highest accumulation totals, and an average of 638 ± 110 degree days between broods was used as a standard. In New Zealand, Prestidge (1992) documented an average of 802 ± 52 degree days between broods from only three locations that were sampled over two growing seasons.

For this study, based on flight activity/captures an average of 933 DD accumulated between fall and spring broods during 2011/12, 665 DD accumulated between fall and spring broods during 2012/13, and 836 degree days accumulated between the first and last peak spring captures in Marland during 2013. The pheromone traps appear to be very attractive to even low numbers of active male flies in the area, but it is possible that the large variations in calculated degree days accumulated among sites within years could reflect sampling inefficiencies at low densities. Buntin and Chapin (1990) mentioned that calculations of degree day accumulation between Hessian fly broods in Georgia was likely due to sampling error. For this current study, portions of each emerging brood quite possibly were not detected on sticky traps as only one trap was placed at each location in an attempt to cover Oklahoma's wheat growing regions. The inability to detect such flight periods compromises the biofix point's accuracy when used to calculate degree day passage, but this approach is likely more efficient than dissecting large numbers of wheat tillers when populations are low. For now, and for practical purposes, the lowest values (~500 DD) observed during the 2-yr pheromone trapping study should be used to plan future research studies, and potentially for management (timely foliar applications) in areas where Hessian fly is perennially at severely high levels. The lowest value should be used because it will allow the producer to begin observation or management actions prior to the initiation of spring flight.

As mentioned above, it is commonly thought that a large precipitation event can trigger the emergence of Hessian fly adults from puparial cases (Flanders et al. 2013, Packard 1928).

Precipitation is obviously important in wheat systems for many reasons including the production of new vegetation for Hessian fly to feed upon. Some large emergences have been detected in California following long drought periods interrupted by heavy rains (Packard 1928). However, based on pheromone trap capture data, correlations between rainfall events and male flight activity were not obvious. As suggested by Lidell and Schuster (1990), a model that incorporates both precipitation and the accumulation of degree days might best predict the beginning of flight periods in areas where the Hessian fly is a pest.

Implications for Management of Hessian Fly in the Southern Plains. Synthetic pheromones can be used for Hessian fly monitoring, scouting, assessment of virulence and potentially for the reduction of pest populations (Anderson et al. 201, Chen et al. 2014). Initially, producers could use pheromone trapping to confirm the presence of Hessian flies in their farming system and plan for management activities (Insecticidal seed treatments, foliar insecticides, crop rotation, resistant cultivars). Currently, however, the relationship between male captures and subsequent damaging larval infestation has not been described. It is also possible that pheromone trapping removes males from a wheat system which may prevent mating and subsequent production of damaging larval infestations. This idea, which clearly needs further study, was initially supported by the high male capture counts in Marland and very low larval populations in adjacent susceptible wheat.

Planting wheat after the 'fly-free date' is based on the reasoning that Hessian fly flight and activity essentially ceases during the winter months after the first freeze in autumn, and fly-free dates are stratified from north to south (Tooker 2012, Chen et. al 2009). For example, northern Pennsylvania wheat fields were recommended a planting date of September 22 whereas the southern fields were recommended October 1 (Tooker 2012). The average first freeze in central Oklahoma from 1891-2004 in central Oklahoma is November the 4 (NOAA 2012), but wheat planted after November will not realize full forage or grain yield potential (Buntin et al. 1992, Kansas State University Extension 1997). During the pheromone trapping study, flies were caught as late as 12/4/12 in Marland, which was well after the freeze for that fall, and well after the recommended fly free planting date for the region (October 25). Thus it seems that planting after the fly-free planting date provides limited benefits in Oklahoma than in Northern states where freezing temperatures during fall eliminate the threat of incoming adult Hessian fly populations.

Producers may be able to use pheromone trapping to monitor periods during a growing season that Hessian fly flight occurs. This may better allow producers to properly time the applications of foliar insecticides in susceptible wheat. Based on the end of fall flight, producers can predict approximately when Hessian fly will begin again during spring using the DEGDAY.xls and compare with averages for their region (Foster and Taylor 1975, Zalom et al. 1983, Snyder 2005). The correct timing of insecticide application (flight and oviposition) is paramount because preemptive applications of short-residual compounds can be effective at limiting population numbers. In Oklahoma, especially during the spring, multiple applications over a three month spring period would be necessary to eliminate a population(s) within a wheat field but this level of suppression would not be economically justifiable. The fall period of Hessian fly flight is considerably smaller in both magnitude and duration and a single foliar application might be effective at reducing a local population if timed with flight initiation of a brood. This management approach must be evaluated to (1) establish the cost-benefit relationship (yield savings vs insecticide cost) associated with suppression of the autumn fly population, and (2) to avoid unnecessary insecticide applications which could disrupt biological suppression of key pests of wheat (Bullock 2004, Schuster and Lidell 1990, Giles et al. 2003, Appendix 2). Correct timing of insecticide applications is critical because there is little that can be done after an infestation has been established.

The application of a fertilizer during the growing season after plants have established is known as “top dressing” which is if often applied in Oklahoma around February prior to the formation of the seed head. Occasionally, an insecticide is applied simultaneously for convenience to reduce potential inputs costs during the spring. Cold temperatures have been shown to lengthen the residual of pesticides (Royer et al. 2011) and if the residual effectiveness is lengthened enough by the cold temperatures such that they still kill emerging Hessian fly adutls, this approach could be a cost-effective way of managing Hessian fly populations within a field. Clearly, further investigation need be performed to establish a link between topdressing applications of fertilizers coupled with insecticides and the subsequent survivorship of Hessian fly populations.

Planting a resistant cultivar remains the most effective approach for preventing damage from Hessian fly populations (Buntin et al. 1992, Royer and Giles 2011, DeWolf et al. 2013). The incorporation of resistant cultivars as a long-term strategy would further add to the ability of cultural, chemical, and biological control to work synergistically at preventing Hessian fly buildup in wheat systems. Pheromone trapping provides information on Hessian fly activity in an area, but also allows for rapid biotype assessment of local Hessian fly populations (Chen et al. 2014) to allow for deployment of effective resistance as the virulence of fly populations change over time (Ratcliffe and Hatchett 1997, Johnson et al. 2004, Chen et al. 2009).

Conclusions

Hessian fly pheromone baited sticky traps were used in this study to characterize the seasonal flight patterns of adult Hessian fly males in Oklahoma. Hessian fly flight in Oklahoma can be characterized by two main flight periods during a single winter wheat growing season; a small fall and an extended spring flight. The fall flight likely serves as the founding population in wheat and in one location there were two peak activity periods. No flight activity was detected from early December – mid February over the two year study, which suggests that winter temperatures are too cold for Hessian fly activity. The larger spring flight began in most of the locations sampled by mid to late March and continued until wheat matured and was harvested, but flight activity was extremely variable among sites. During spring 2012, for most locations, an extended single brood emergence appeared to occur suggesting a single spring generation. However, during spring 2013, multiple flight peaks occurred at many locations suggesting more than one spring generation. Many more growing seasons would need to be sampled to be able to efficiently characterize the plasticity of Hessian fly flight and link these flights to actual field larval populations.

Based on results from previously published studies (Buntin 1990, Prestidge 1992), use of degree day accumulation at the end of fall flight in Oklahoma allowed for a conservative estimate of spring flight initiation of the subsequent Hessian fly brood. Hessian fly began emerging (captures in pheromone traps) after ~500 degree days had accumulated but this value ranged up to 1329 DD in western Oklahoma. A future model that incorporates both precipitation and degree days might best predict the beginning of the spring flight period for Hessian fly.

Actively monitoring Hessian fly flight with pheromone baited sticky cards will likely aid in a producer's abilities to manage this sporadic pest. Producers could use this technique to confirm the presence of Hessian flies in their farming system and plan long-term management strategies that ensure sustainable suppression of this pest.

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APPENDICES

Table A1.1

	2011								2012														
Column1	10/21	10/28	11/4	11/10	11/17	12/1	12/8	12/27	1/5	1/11	1/18	1/23	1/30	2/6	2/16	2/24	3/13	3/29	4/13	4/25	5/7	5/17	5/28
Marland NT 1	0	91	2	11	0	0	0	0	0	0	0	0	0	0	0	2	3	585	864	981	71	23	0
Marland NT 2	0	22	1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	820	495	1794	14	0	0
Blackwell CT 1	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	414	612	23	22	3	0
Blackwell CT 2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	369	513	0	1	0	0
El Reno NT E 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	24	33	81	107	1	0	0
El Reno NT E 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	45	639	297	151	0	1	0
El Reno NT W 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	360	44	7	0
El Reno NT W 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	x	x	x	x	x
El Reno P/G 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	18	18	1	0
El Reno P/G 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	46	0		9	3	
El Reno G 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	2	1	14	58	24	2
El Reno G 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	15	0	1	0	0
Perkins CT 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	58	324	333	9	1	0
Perkins CT 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	91	135	414	45	0	0
Perkins G 1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	9	87	405	171	1	2	0
Perkins G 2	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	5	0	10	234	195	11	2	0
Woodward CT 1	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0	0
Woodward CT 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0
Woodward VT 1	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	19	0	0	0
Woodward VT 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Microsoft Excel Spreadsheet containing all flight trapping data for the 2011/12 growing season.

Table A1.2

	2012										2013																
	10/22	10/30	11/6	11/13	11/20	11/27	12/4	12/9	12/14	12/21	1/4	1/14	1/22	1/28	2/11	3/6	3/15	3/25	4/5	4/18	5/1	5/8	5/20	6/2	6/11	6/19	6/26
Marland NT 1	0	0	18	0	0	39	4	0	0	0	0	0	0	0	0	0	0	1	0	0	68	32	29	23	2	4	0
Marland NT 2	0	0	7	0	0	36	19	0	0	0	0	0	0	0	0	0	0	0	142	35	117	105	9	157	26	0	0
Marland NT 3	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	58	66	16	16	18	0	14	44	7	0
Blackwell CT 1	0	0	0	0	1	0	1	0	0	0	0	0	0	0	0	0	0	2	1	1	5	4	0	36	423	0	0
Blackwell CT 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	6	11	13	x	675	0	0
Perkins CT 1	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	19	1	5	13	1	20	3	0	0
Perkins CT 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6	0	8	4	10	3	19	18	3	0	0
Cashion NT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	7	13	89	36	7	0
Cashion CT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	65	49	1	0
El Reno CT 1	0	0	0	0	0	1	4	0	0	0	0	0	0	0	0	0	0	2	4	7	6	8	2	21	2	0	0
El Reno CT 2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	13	15	8	6	0	11	0	0	0
El Reno NT 1	3	0	0	0	0	0	43	0	0	0	0	0	0	0	0	0	0	6	5	12	6	7	0	28	0	0	0
El Reno NT 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	25	11	6	12	6	32	1	0	0
El Reno P	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0
Woodward VT				2	1	0	0	0	0	0	0	0	0	0	0	0	0	0	15	5	1	0	0	0	0	0	0
Woodward CT				0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	1	2	0	0	0	0	0	0
Altus NT													0	0	0	0											
Altus CT													0	0	0	0											

Microsoft Excel Spreadsheet containing all flight trapping data for the 2012/13 growing season.

Appendix 2

Hessian Fly Parasitoid Sampling and Identification

Introduction

A small additional study was conducted in the spring of 2014 in an attempt to identify and characterize Hessian fly parasitoid activity and species composition. There have been no prior investigations in Oklahoma regarding Hessian fly parasitoids.

Materials and Methods

Hessian fly puparia were gathered by taking whole plants from an infested field in Anadarko, Oklahoma on 4/4/14. Samples were collected in April when wheat was developing towards maturity and temperatures were within the Hessian fly's developmental thresholds. Five areas (~ 10 m^2) were randomly sampled using procedures described by Schuster and Lidell (1990). Schuster and Lidell (1990) only found parasitoids of the Hessian fly during spring months in Northern Texas, and therefore sampling for this preliminary study was restricted to April 2014. 500 tillers were examined to determine the intensity of the Hessian fly infestation at this location. To document the percentage parasitism of puparia, a subsample of 100 culms were chosen and 250 puparia were removed from damaged tillers and stored in alcohol to be dissected to assess the parasitism percentage (Schuster and Lidell 1990, Pons et al. 2013). Effective parasitism (Pe) was calculated as Pe = [(number of parasitoids observed/ number of Hessian fly pupae observed) x 100] (Pons et al. 2013). Puparia were dissected under a Leica S8 APO 80x stereomicroscope and larvae within were identified as either being Hymenopteran or Dipteran. The presence of jointed antennae, a well-developed head capsule, well developed compound eyes, and clearly distinguishable three segmented body differentiated Hymenopteran parasitoid larvae from Hessian fly larvae (See Figure 5).

An additional assessment was performed to assess the percentage of apparent parasitism (Stansley et al. 1997, McAuslane et al. 1993). Dead tillers filled with Hessian fly puparia were removed from plants and placed inside transparent air tight plastic boxes with cotton balls soaked with deionized water to maintain high relative humidity. Containers were kept at a constant 20ºC 14:10 (L:D) photoperiod. Hessian fly began emerging the day after samples were obtained and parasitoids began emerging after 10 days, and tillers were monitored for 6 weeks until no additional emergence occurred. Parasitoids and Hessian fly were collected daily using an aspirator and stored in alcohol, and identified using morphological characteristics (Riley 1885, Gahan 1933). Percentage apparent parasitism was calculated by P = 100x Pe ÷ (We + Pe), where Pe represents the number of parasitoids that emerged and We represents the number of Hessian fly that emerged (McAuslane 1993, Stansley et al. 1997).

Results and Discussion

Of the 500 tillers examined, 86 Hessian fly puparia were found which is relatively low and below the economic injury level proposed for Hessian fly in wheat systems (Alvey 2009). Hessian fly larvae found within pupal cases were observed in multiple stages of development from newly pupated larvae to fully formed adults that were killed during emergence (See Figure 7). Of the 250 puparia that were removed from live wheat plants and later dissected, 12 contained Hymenopteran larvae. Similarly, wasp larvae recovered from pupal case dissections spanned a spectrum of developmental stages from early instar larvae barely discernable as being Hymenopteran to melanized individuals close to emergence. If both vacated and viable puparial cases are counted, the effective percentage parasitism rate was 12/250 or 5% (See Table 3) (Pons et al. 2013). 94 pupal cases were void of any larvae likely due to emergence before sampling. Of the viable puparia that were dissected 12/156 or 8% were effectively parasitized by a Hymenopteran.

236 adult Hessian fly and 90 parasitoid wasps emerged from puparia within the dead stem sections that were placed in air tight containers. Thus the apparent parasitism rate calculated from live rearing was 90/236 or 28% (See Table 4). The live wasps emerging from Hessian fly puparial cases were identified as *Trichomalopsis supbaptera* (Hymenoptera: Family) based on morphological characteristics. *Trichomalopsis subaptera* was known as *Mesius subapterus* as well as *Homoporous subapterus* in the publications where it was first described (Riley 1885, Gahan 1933). This species represented 100% of the parasitoids that emerged within air-tight containers.

Only 5% of larvae removed from puparial cases could be identified as Hymenopteran, however, 28% of emerging insects within the airtight containers were be identified as Hessian fly parasitoids. This large difference may be due to Hessian flies that remained within wheat tillers that could have been in extended diapause. Quantification of percentage parasitism in a field can be difficult because individuals whose developmental stages aren't apparent to the observer will go unnoticed. Dissection of Hessian fly puparial cases could consistently underestimate the percentage parasitism of a field when compared to live rearing because individuals are killed soon after sampling and natural enemies still in egg or early instar stages might well remain unnoticed.

The Hessian fly parasitoid *T. subaptera* was described for the first time in Oklahoma, and comprised 100% of live adult individuals captured during rearing (See Figure 6) (Riley 1885, Gahan 1933). This species was discovered in low densities in Northern Texas and only in Hunt and Denton Counties in 1987 (Schuster and Lidell 1990), but in far fewer numbers than *Homoporous destructor* and *Eupelmus allynii*. *T. subapterus* has been reared from Hessian fly puparia collected in Idaho but was not found in Washington (Bullock 2004, Pike et al. 1983). *Trichomalopsis subapterus* has been characterized as having the ability to reduce the number of individuals within a Hessian fly population. There is no record of this organism having been introduced as a means of controlling Hessian fly population numbers prior to 1978 (USDA 1978).

It is assumed that *T. subaptera* then is probably native to the area. Further investigations describing the impact of this natural enemy in the Southern Plains are warranted, especially studies that integrate plant resistance and parasitoid conservation for long term sustainable Hessian fly suppression.

Table A2.1 Rate of effective parasitism from 4/4/14 near Anadarko, Oklahoma.

Table 3. Total Parasitism: Dissections	
Puparial Cases Dissected	250
# Empty Puparial Cases	94
# Hessian Fly Immatures	144
Parasitoids	12
Total Parasitism %	5%
Total Parasitism as calculated by Pons et al. 2013	

Effective parasitism (Pe) was calculated as Pe = [(number of parasitoids observed/ number of Hessian fly pupae observed) x 100] (Pons et al. 2013).

Table A2.2 Rate of apparent parasitism found on 4/4/14 near Anadarko, Oklahoma.

Table 4. Apparent Parasitism: Live Rearing	
# Hessian fly adults	236
# Parasitoid adults	90
Apparent Parasitism %	28%
Apparent parasitism as calculated by McAuslane et al. 1993	

Percentage apparent parasitism was calculated by P = 100 x number of parasitoids emerged ÷ (number of Hessian fly emerged+ number of parasitoids emerged) (McAuslane 1993, Stansley et al. 1997)

Figure A2.1 An example of the hymenopteran larvae found through dissections of wheat plants. Jointed antennae, a well-developed head capsule, well developed compound eyes, and clearly distinguishable three segmented body are present.

Figure A2.2. The Hessian fly parasitoid *Trichomalopsis subaptera* was described for the first time in Oklahoma, and comprised 100% of live adult individuals captured during rearing

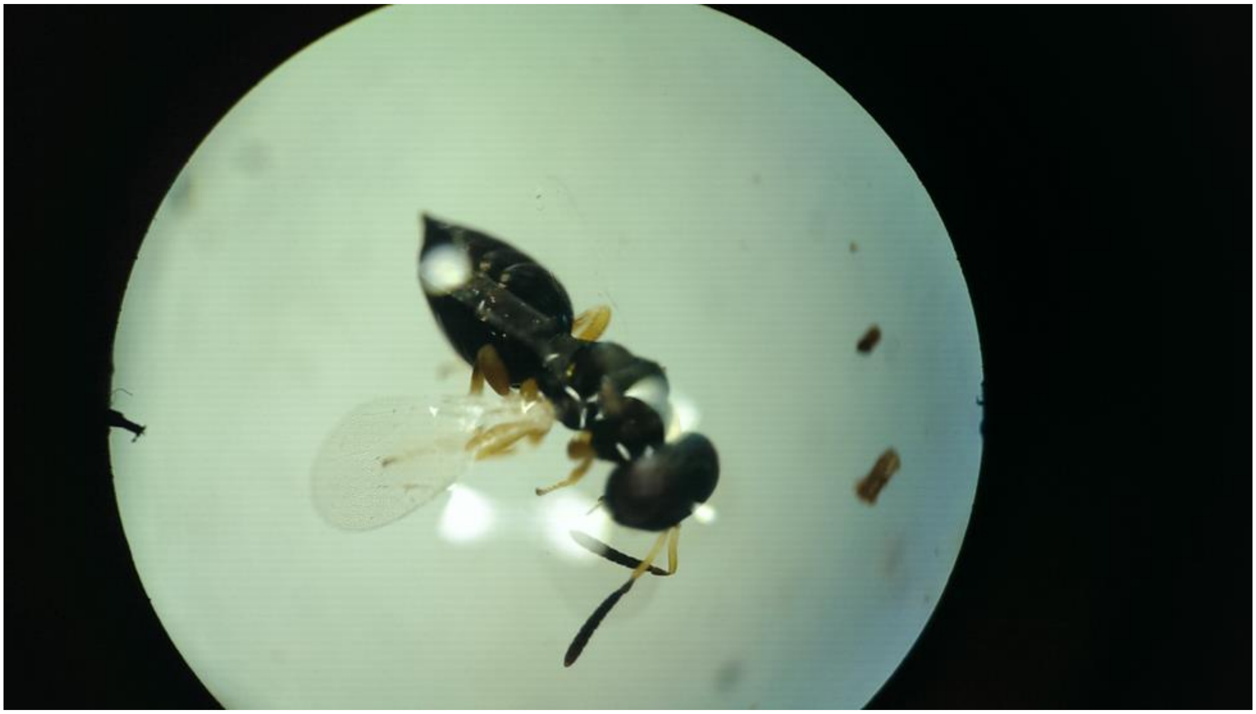

Figure A2.3. Hessian fly larvae found within pupal cases were observed in multiple stages of development from newly pupated larvae to fully formed adults that were killed during emergence. A Hessian fly preserved during emergence exemplifies this.

VITA

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