CHARACTERIZATION OF THE GRAPE PEST COMPLEX IN OKLAHOMA

By

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CHAPTER I. GENERAL INTRODUCTION

Pest Identification

Grape production is on the rise in Oklahoma. This increased interest has necessitated that the pest complex be characterized. In addition, management tools and practices were developed for the agricultural producers of the state. This study undertook the task of characterizing the pest complex attacking grapes in Oklahoma to optimize product yields. An extensive literature review revealed major pest species that occur in surrounding states (Arkansas, Texas, and New Mexico).

Evaluation of the Grape Insect Pest Complex

The objective of this study was to characterize insect pests present on grapes throughout seasonal growth stages of the plant in Oklahoma. A preliminary literature review indicated that three major insect pests of grapes should be anticipated; grape berry moth, *Endopiza viteana* Clemens, grape root borer, *Vitacea polistiformes* (Harris), and various species of leafhoppers and sharpshooters (Family: Cicadellidae). Relative to grape berry moth, vineyards can be assessed as to potential risk of attack by larvae. Vineyards rated as high risk have a history of high grape berry moth injury and > 50% of vineyard perimeter is adjacent to wooded areas. Low-risk is assigned to vineyards that have < 25% of the vineyard perimeter adjacent to woods and the historical presence of grape berry moth is low (personal communication – D. Johnson - Cooperative Extension Service).

A predictive monitoring tool has been used for the management of grape berry moth in Oklahoma. Using species-specific pheromone trapping techniques, monitoring for the grape berry moth began April 1, 2002 and accumulation of degree-days began after first capture (bio-fix). This study will explore the accumulation of degree-days.

beginning at various dates, to determine the optimal starting date for predictive models, resulting in a useful tool for producers in Oklahoma.

Pheromone traps were also used to monitor for the grape root borer. Three pheromone traps transecting the vineyard in a diagonal manner were placed on the top wire by June 1. If adult grape root borers were captured during June, scouting for pupal skins along the soil surface began July 1. If grape root borer is found to be a major pest species, different cultural practices will be explored later to determine the most beneficial and practical approach for managing this insect.

Yellow sticky traps were used to monitor for various leafhopper species, including those suspected of transmitting Pierce's disease. Finally, general scouting was performed to identify any pest not attracted to yellow sticky traps or species specific pheromones.

Evaluation of a Degree-Day Model for the Grape Berry Moth

An existing model used to predict life stages of economic importance of the grape berry moth was evaluated in a two-year study in Oklahoma. The existing model incorporates a starting date based on a bio-fix (accumulation of degree days after first capture) that is widely popular among producers residing in the mid-west and southern states. Five alternative methods of calculating degree-days were compared to the traditional method of accumulation. The model with the best fit can be suggested for use throughout the plains states. The result will save producers time and money in their management practices. In addition, reduced sprays will be less taxing on the environment.

Evaluation of potential vectors of *Xylella fastidiosa*

The bacterium, which causes Pierce's Disease, *Xylella fastidiosa* is not known to occur in Oklahoma. Early detection of vectors of this pathogen will allow for timely eradication and more effective management of vineyards by producers. Sampling began in April in targeted regions of the state. A survey of each site was conducted using six yellow sticky traps placed in a diagonal across the vineyard at two height levels, the lower portion of the cane and higher among the vegetation. Lower traps are intended to capture the glassy-winged sharpshooter, *Homalodisca coagulata* Say, which tend to feed on lower portions of the cane, the traps placed higher (upper wire) were intended to monitor for green sharpshooter, *Draeculacephala minerva* Ball and blue-green sharpshooter, *Graphocephala atropunctata* Signoret. Traps were examined twice weekly and replaced by new traps during each inspection. Leafhoppers, sharpshooters and similar organisms were identified, counted and documented according to time and place of capture.

Explanation of Thesis Format

The general introduction is followed by a literature review (Chapter II). Chapters III and IV are devoted to individual papers to be published. Chapter V is a general summary. References are provided for citations in the literature review and papers to be published. The first paper (Chapter III) is an evaluation of the grape berry moth degree day model used in Oklahoma. The second paper (Chapter IV) is a study of the vector/disease complex involving Pierce's Disease and its' status in Oklahoma.

CHAPTER II. REVIEW OF PUBLISHED LITERATURE

The Pest Complex

In Oklahoma, the grape industry is in its infancy. Before identification of the major pests affecting grapes could be undertaken a preliminary literature review was completed. A wide range of pest species attack grapes in North America, including; the grape berry moth, *Endopiza viteana* Clemens, the grape root borer, *Vitacea polistiformes* (Harris), and various leafhoppers and sharpshooters. This review of the literature will cover the most important insect pests found to affect grape production throughout the Southern Plains states.

The Grape Berry Moth

The grape berry moth, a major pest of cultivated grapes, is native to eastern North America where it still occurs on wild grapes. Its present range of distribution is the territory east of the Rocky Mountains (Taschenberg et al. 1974), wherever wild or cultivated hosts occur. In many cases, the grape berry moth can cause serious economic damage (Gleissner 1943). Grape berry moth feeds only on grapes and completes one to four generations per year.

Adult moths begin to emerge from overwintering pupae in early- to mid-April, before the blossom period. Location and temperature influence the timing of occurrence and the number of generations per year (Sanders and DeLong 1921). For example it is thought that *E. viteana* is bi- to tri- voltine in the Lake Erie region (Gleissner and Worthley 1941), whereas areas in southern latitudes such as Missouri and Virginia, rarely exhibit less than four generations (Tobin et al. 2003). In addition, heat unit accumulation plays a very important role in development (Baskerville and Emin 1969).

The adult grape berry moth is small and has an inconspicuous brownish appearance (Dozier and Butler 1929). When at rest, the grape berry moth is 6mm in length and has a wingspan of 9 to 12mm. The forewings are gray at the base, producing the appearance of a slate grey saddle across the back. The coloration becomes cream-colored with brown patches towards the tips. The smaller smoky-brown hind-wings are hidden underneath the forewings when the moth is at rest. The body color is brown. Moths rest during most of the day and become active around mid- to late afternoon. Their rapid, zig- zag flight can be observed until after dusk (Gleissner 1943).

Early in the spring, eggs of the grape berry moth are laid singly on buds, stems, and newly-formed berries (Hoffman and Dennehy 1989). After berries have matured, later in the season, eggs are laid directly on maturing fruit. Depending on temperature, eggs hatch after 4 to 8 days (Hoffman et al. 1992). The opaque white eggs are oval, scale- like, and measure only 0.7 mm across (Driggers 1935).

Newly hatched larvae are creamy white with a dark brown head and thoracic shield (Ingerson 1920). The larval body becomes greenish and eventually turns purple as it grows. The head of the mature larva is light brown but the thoracic shield remains dark colored. Mature larvae measure 10 mm in length (Biever and Hostetter 1989).

The first larvae in the spring feed on tender stems, blossom buds, and the newly set berries. Larvae can be found feeding inside the protective webbing, often involving the entire cluster (Tobin et al. 2001). As berries mature to approximately 3mm in length, larvae begin to burrow into the fruit. Second generation larvae feed only on the berries. They usually enter the fruit where berries touch, or where the berry is joined to the stem. There does not appear to be any preference between the selected sites for feeding. After

larvae have entered the fruit, they feed just below the skin but eventually the inside of the berry is attacked. Often, larvae feed successively on 2 to 3 berries. Up to seven berries can be destroyed by a single larva.

First-generation larvae that reach maturity move to a leaf where they cut out a circular flap to construct a pupation chamber. The majority of fully developed second-generation larvae spin down to the ground where they construct pupal cells for overwintering in fallen leaves (Tobin et al. 2002). The grape berry moth overwinters in the pupal stage. The pupa is 5 mm long and is either light-brown with a green shade on the abdomen or entirely dark green (Gleissner 1943, Luciani 1987).

Damage caused by larvae of the first generation can be serious. A single larva can destroy a dozen or more potential berries by feeding on buds, flowers, and newly set fruit (Driggers 1935). Due to the timing of maturation in the grape plant some of the emerging late first generation and all second-generation larvae feed only on the berries. Often, a reddish spot surrounds the point of larval entry. This discoloration can extend over half of the surface of an otherwise green berry and affect the brix (percent sugar) of the berries. Injured berries ripen prematurely, split and shrivel.

Feeding by grape berry moth larvae also creates infection sites for rot organisms and invites attack by fruit flies, *Drosophila* sp. Infestations by the grape berry moth can vary greatly from year to year and are often uneven across a vineyard. Webbing produced by the larvae prevents injured berries from dropping to the ground resulting in extra pathogens being closely associated with surrounding berries (Biever and Hostetter 1975). Larval feeding directly reduces yield and contaminates the crop (Dozier and Butler 1929).

If populations of grape berry moth are low enough, injured berries can be removed by hand. Cultural methods have been used in the past to reduce populations of overwintering grape berry moths. In the fall, control can be achieved by gathering and destroying abscised leaves that contain pupal cells. This practice reduces the number of adults emerging the following spring. Covering leaves containing cocoons under the trellis with 2.5 cm of compact soil will also prevent emergence. This operation must be completed two weeks ahead of the bloom period. If the grape berry moth is an annual or severe problem, postbloom application of insecticide may be necessary. Pheromone traps have been used to monitor emergence and activity of male moths (Danko and Jubb 1983, Roelofs et al. 1971). In addition, the environment can be flooded with pheromone to confuse and disrupt male moths (Taschenberg and Roelofs 1976). Use of pheromone traps may be helpful in improving the timing of scouting and subsequent control measures against this grape pest.

The Grape Root Borer

The grape root borer, *Vitacea polistiformes* (Harris), has the possibility of becoming a severe pest of grapevines anywhere they grow in the United States. This species overwinters as a larva in two different stages of development. The life cycle takes two years to complete (some studies indicate a three-year cycle), and almost all of this is spent as a larva feeding on grape roots (Olien et al. 1993).

Larvae bore into roots and crowns below the soil surface, reducing productivity of the vine. Roots may be hollowed and sometimes packed with frass. Vines eventually die from disruption of nutrient transport, but there may also be increased susceptibility to cold injury. Young larvae are spread throughout the root zone, while older larvae are

found primarily in large roots near the soils surface. Ninety percent of the pupae are often found within 35 cm of the trunk at a mean depth in the soil of 9-10 cm. A lack of plant vigor is usually the first sign of infestation by larvae of the grape root borer. Another indication, in late July and August, is the presence of cast pupal skins protruding from the soil near the base of the trunk. (Harris et al. 1994).

Full-grown larvae are approximately 25 mm long, white, and possess a brown head. Beginning in June, larvae leave the roots and pupate in cocoons near the surface of the soil. Adults emerge 35-40 days later, about the first week of July. The greatest numbers of pupae are present during the last two weeks of July. Moths are wasp-like in appearance. The body is generally brown. The top of the head is orange; antennae are orange with brown-black markings; the abdomen is dark brown with reddish-brown markings, with a very narrow yellow band on the posterior edge of segments two, four, and sometimes six. Legs are orange with brown-black markings. The forewings are dark and mostly opaque. The hind wing is generally more transparent than the forewing (Olien et al. 1993).

Grape root borer moths are daytime fliers. After flying for several days, females begin oviposition on grape foliage, canes, and weeds. Each female lays an average of 300 eggs. About two weeks after eclosion, first instar larvae drop to the ground and tunnel to roots. The greatest natural mortality occurs at this point in the life cycle (Webb et al. 1992). Only 1.5-2.7% survive this first stage because of predation, parasitism, and desiccation; however, once established in roots, mortality is very low. Infested vines are usually encountered randomly across a vineyard. Larvae do not travel far in the soil, usually remaining on the roots of a single vine.

Control of this pest is difficult. Contact insecticides are ineffective against subterranean larvae, although soil injection with fumigants has shown promise. Recently, some soil barrier treatments have been shown to be effective. An effective cultural control method involves mounding soil beneath vines after borers have pupated, thus preventing successful emergence of moths. These ridges can be leveled in the late fall or early spring. Timing of this cultural control method is important because mounding soil too early allows larvae to tunnel up into the ridge before pupation. Effective weed control also appears to be important in borer management because it increases larval mortality and decreases oviposition at the exposed soil surface. When vines are infested, nitrogen fertilization may help overcome effects of damage.

Pierce's Disease Complex

Pierce's disease of grapes, caused by the bacterium *Xylella fastidiosa*, infects grapes in the early spring. Symptoms of Pierce's disease appear as water stress in midsummer (Davis et al. 1978). This appearance is caused by blockage of the plants water-conducting system (xylem) by the bacteria (Davis et al. 1980). Occurrence of four symptoms in mid- to late-summer (Hill and Purcell 1997) aid in identifying the presence of Pierce's disease (Frazier 1965). First, leaves become slightly yellow or red around the outside margins. Eventually, these margins dry or die out and necrotic edges form. These edges are often referred to as "concentric zones". Second, fruit clusters may shrivel or raisin. Next, dried leaves fall from the cane, leaving the petiole intact (a key characteristic of the disease) (Hewitt et al. 1949). Finally, wood on new canes matures irregularly (Davis et al. 1978), resulting in alternating patches of green and brown vines.

Leaf symptoms vary among grape varieties. In many cases, late in the first season of infection, only one or two canes will show symptoms of Pierce's disease. Symptoms gradually spread along the cane from the point of infection out towards the end. Symptoms spread slowly towards the base of the plant (Freitag 1951).

By mid-season some or all of the fruit clusters on infected canes may wilt and dry, ruining the harvestable commodity. Tips of canes and roots may exhibit these die back symptoms. After appearance of symptoms, vines of susceptible varieties deteriorate rapidly. Shoot growth of infected plants becomes progressively weaker as symptoms become more pronounced (Frazier 1965).

There is no curative treatment for grapevines with Pierce's disease. Current control strategies in California are based on preventing immigration of vectors into vineyards during the spring by spraying riparian vegetation with insecticides, and management of adjacent vegetation to eliminate hosts of *X. fastidiosa* and sharpshooters (Goodwin and Purcell 1990, Purcell and Feil 2001). Breeding for resistance to Pierce's disease has proven to be beneficial for grape production. It is recommended that a sanitation program be initiated if glassy-winged sharpshooter is involved.

Sharpshooter Vectors of Pierce's Disease

The bacterium that causes Pierce's disease, *Xyllela fastidiosa*, lives in the water-conducting system (xylem) of plants (Hill and Purcell 1995a). The bacterium is spread from plant to plant by sap-feeding insects (sharpshooters) that feed on the xylem (Severin 1949). Symptoms appear after a significant amount of xylem becomes blocked by the growth of the bacteria (Krugner et al. 1998). The blue-green sharpshooter, *Graphocephala atropunctata* Signoret, was at one time the most important vector in

California and can be found in the midwestern United States (Hill and Purcell 1995b). The green sharpshooter, *Draeculacephala minerva* Ball, is also present in coastal areas but are more important as vectors of this disease in the Central Valley areas of California. Green sharpshooters are also found throughout the Midwestern United States.

The preferred breeding habitat for the blue-green sharpshooter is riparian (riverbank) vegetation, although ornamental landscape plants and various sources of succulent vegetation may also harbor breeding populations. These insects appear coordinated with their feeding preference as the season progresses, preferring to feed on plants with mature, succulent growth (Purcell 1981). The principal breeding and feeding habitats for blue-green sharpshooters occurs in irrigated pastures, hay fields, or other assorted grasses (Purcell 1975).

Throughout the West Coast of California, the most prolific and efficient vector of Pierce's disease is the glassy-winged sharpshooter, *Homalodisca coagulata* Say (Sorensen and Gill 1996). This insect is becoming a growing concern among grape producers throughout the United States (Brodbeck et al. 1995). The glassy-winged sharpshooter is a serious threat to California vineyards because it moves faster into vineyards, is a strong flier and survives better than the other species of sharpshooters. The glassy-winged sharpshooter is expected to spread northward and become a permanent resident of various habitats throughout northern California (Goodwin and Purcell 1990). It is too early to predict in which regions and habitats within the United States it will become permanently established.

Feeding by the glassy-winged sharpshooter occurs much lower on the cane than other sharpshooters. Late-season (after May-June) infections introduced by the glassy-

winged sharpshooter, may survive the winter. This would enable vine-to-vine spread of Pierce's disease, which up to the present time has not occured in California (Blua et al. 1999). Vine-to-vine spread can cause repeated infections in a season and can increase the incidence of Pierce's disease exponentially, causing extremely rapid infection rates among neighboring plants (Perring et al. 2001, Purcell and Feil 2001). During the winter, glassy-winged sharpshooters also feed on dormant grapevines and have introduced infections into dormant plants under laboratory conditions, proving that the bacteria is capable of being transmitted throughout the year (Purcell and Saunders 1999).

There are cases where vines recover from Pierce's disease the first winter following infection, however the infection may only be latent. In tolerant cultivars, the bacteria spread more slowly within the plant than in more susceptible plants (Purcell 1997). Once the vine has been infected for over a year, recovery is less likely. Young vines are more susceptible than mature vines (Davis et al. 1978). Hybrids vary greatly in susceptibility from rootstock species. Many rootstock species are resistant to Pierce's disease, but the rootstock does not confer resistance to susceptible *Vinifera* varieties grafted on later. Finally, the date of infection strongly influences recovery: late infections (after June) transmitted by blue-green sharpshooters and green sharpshooters may allow the plant adequate opportunity to survive. This is not the case with glassy-winged sharpshooter however, because it feeds on leaves near the base of the cane.

Until more information about the glassy-winged sharpshooter's role in spreading Pierce's disease is available, growers should try to reduce the numbers of sharpshooters present in vineyards at all times (Purcell and Feil 1979). In addition, removing diseased vines as soon as possible when Pierce's disease first appears in a vineyard is critical in

helping reduce infection rate. Early and vigilant disease detection and vine removal is recommended for any vineyards that experience influxes of the glassy-winged sharpshooter (Goodwin and Purcell 1990, Purcell and Feil 2001).

There are currently long-term studies being conducted on the effect of vegetation management in reducing disease incidence and severity in North Coast California vineyards, where grape production is the highest in the United States. Vegetation management has proven to be effective in reducing the damaging spring populations of blue-green sharpshooters (Goodwin and Purcell 1990), and perhaps other sharpshooter vectors.

Controlling the vector in areas adjacent to the vineyard, via insecticide practices, has reduced the incidence of Pierce's disease by decreasing the numbers of sharpshooters immigrating and emigrating from vineyards in early spring. Removing vines that have Pierce's disease symptoms for more than one year can also be effective since these simply serve as harborage for the disease. It is likely that they are chronically infected and unlikely they will recover or continue to produce a significant crop. In addition, removing vines with extensive foliar symptoms on most canes and with tip dieback of canes even if it is the first year that symptoms have been evident, can be beneficial (Purcell 1989). Marking all the slightly symptomatic vines in fall and re-examining them for symptoms the following spring through late summer or fall is a good practice in catching problems early in development. Vines that have symptoms for a second year should definitely be removed (Goodwin and Purcell 1990).

Leafhoppers

The grape leafhopper, *Erythroneura comes* Say, is a pest of grapes from the coasts of California to the plains of the Midwest (DeLong and Severin 1949). Leafhoppers overwinter as adults and are found in spring and summer on basal grape leaves and an assortment of weeds (Frazier and Freitag 1946). The adult grape leafhopper measures about 3 mm in length and exhibits a pale yellow background coloration with distinct dark brown or reddish markings (Hartzell 1913). In April and May, eggs are laid in epidermal tissue on the undersides of leaves. Eggs appear as a bean-shaped, blister-like protuberance that measures less than 1 mm in length (Taschenberg and Hartzell 1949).

Nymphs and adults remove the liquid contents of leaf cells. Removal of these cell contents results in a pale yellow or stippled leaf appearance (Johnson 1914). When populations are high, the entire leaf may appear pale yellow or white (Hartzell 1913). Extensive leaf drop can also occur when leafhopper densities are extremely high. This leaf loss results in sunburned fruit and weakened vines for the following season. Feeding from leafhoppers can also reduce sugar content of berries and spotting of fruit from excrement can also be an unpleasant result. Adult leafhoppers also serve as a nuisance to workers when populations are high at harvest time. Their excrement appears as sticky clumps that darken with age due to oxidation, thus damaging the production of high quality wines. Vines can be fairly tolerant to high populations, and predators and parasites may be able to maintain leafhopper populations below tolerance levels.

Biological control also occurs through natural enemies. Egg parasitoids such as, *Anagrus epos* Girualt, and other *Anagrus* spp., are commonly found in vineyards during part of the season. Green lacewings, *Chrysopa spp.*, Minute Pirate Bugs, *Orius spp.*,

various Lady Bird Beetles, *Hippodamia spp.*, spiders and mites all help control economic populations. Cultural methods can be initiated within vineyards and the surrounding areas by removing weeds. This should be done in the spring before vines start to grow, thereby reducing leafhopper populations that might disperse to new grape foliage. The use of a flail mower before budbreak is particularly effective in removing excess vegetation which may serve as a harborage for potential vectors.

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CHAPTER III. EVALUATION OF THE GRAPE BERRY MOTH DEGREE DAY MODEL

Abstract

Predictive models for anticipating economically important events in the life cycle of grape berry moth, *Endopiza viteana* Clemens, were evaluated in a two year study in Oklahoma. In 2002 and 2003, monitoring was conducted in three locations. Trapping began April 1 and ended August 15. Twice weekly counts of male moths were recorded for grape berry moth. In addition, scouting for phenological stages of the grape berry moth was recorded. Developmental models for the grape berry moth were evaluated to determine the accuracy of model predictions. Models initiated on January 1 of each year, or those begun based on developmental temperature threshold (10°C) yielded the most precise predictions of phenological events of the grape berry moth. These two predictive models were significantly more accurate when comparing predicted and observed phenological events than the previous standard of using first capture (bio-fix) of adult males to initiate accumulation of degree days. In addition, models initiated on January 1 or at developmental threshold also preceded phenological events and predicted their arrival nearly two weeks prior to the other models. These latter two findings are more desirable for development of IPM programs because they anticipate arrival of damaging stages of grape berry moth and coincide better with observed phenological events.

Introduction

The grape berry moth, *Endopiza viteana* Clemens, is considered one of the most severe pests of grapes in North America. The grape berry moth attacks native grape species such as *Vitis labrusca* and *Vitis riparia* Micheaux. Grape berry moth also exploits most varieties of cultivated grapes in North America. Every year, serious economic damage to cultivated grapes is caused by larvae of the grape berry moth. *E. viteana* is native to North America, where it is distributed in the United States east of the Mississippi River (Gleissner 1943). Evidence of populations also exist throughout the southern plains states.

The current popular cultivars for Oklahoma include Cabernet Sauvignon, Chardonnay, Cynthiana, Riesling, and Sauvignon Blanc. Although many species of grapevine occur throughout the world, and as many varieties of each species abound, almost all grapes produced for wine, juice, jams, raisins, or table use are either of European or North American origin. Nearly 95% of these grapes originated from *Vitis vinifera*, the European species. This species contains cultivars used for wine-making (Cabernet Sauvignon, Chardonnay, Pinot Noir, Zinfandel, and Carignane), other cultivars grown for table grapes (Emperor, Tokay, Perlette, and Ribier), and several cultivars grown for the dried fruit market (Thompson Seedless, Black Corinth, Muscat of Alexandria). The two species of North American grapes that are the most economically important include *Vitis labrusca* (var. Concord) and *Vitis rotundifolia*.

Damage by larvae of the first generation grape berry moth can be serious, since a single larva can destroy a dozen or more potential berries by feeding on buds and flowers. Late first and all second-generation larvae feed only on the berries. The appropriate

generation can be assigned to larvae based upon the width of the larval head capsule and the maturity of the infested plant, (first instars - 0.206 mm; second - 0.296mm; third -0 .489; and fourth - 0.767) (Gleissner 1943).

The second-generation of grape berry moth is potentially more damaging than the first. Single larvae can destroy six berries in a cluster, and several larvae may inhabit a single cluster. Injured berries ripen prematurely, split and shrivel. Webbing produced by larvae prevents berries from dropping. Larvae feeding directly on berries reduces yield and contaminates the crop. More importantly, feeding by larvae creates infection sites for fruit rots and feeding by fruit flies. At harvest, severely infested bunches may contain several larvae and many berries that are completely hollowed out. Often, the grape cluster is covered with bunch rot fungi, infested with fruit flies and appears unhealthy.

In most cases, synthetic sex pheromones are used to monitor for presence of grape berry moth populations (Biever and Hostetter 1989). The presence of a sex pheromone in *E. viteana* was first reported by Roelofs and Feng (1968) and its chemical structure was identified as (Z)-9-dodecenylacetate (Z9-12Ac) (Roelofs et al. 1971). Traps are baited with this compound and used by growers to monitor for flight activity of male grape berry moth (Biever and Hostetter 1989, Hoffman and Dennehy 1989). Taschenberg et al. (1974) determined that rubber septa containing 10-30 μg of Z9 – 12Ac were more effective than other blends. Presently, a blended form of Z9 – 12Ac and (Z) – 11 – tetradecenyl acetate (Z11 – 14Ac) is used for mating disruption formulations to control grape berry moth and in traps used for monitoring (Hoffman and Dennehy 1989). The grape berry moth, like all insects, is a temperature dependent organism. Therefore, it is important to understand the relationship between insect development and ambient

temperature (Tobin et al. 2002). Sensible insect pest management relies on control tactics for accurate forecasting and phenological prediction, and the understanding of temperature-dependent development is paramount to many successful pest management programs (Tobin et al. 2001). In many instances, linear degree-day models are used, in which species-specific lower base temperature thresholds are subtracted from the daily average temperatures to yield a degree-day total. Most of the literature on grape berry moth conducted in laboratory studies indicates that the egg-to-adult degree-day requirements are approximately 423.9 degree-days, based on the Celsius scale, with a basal developmental temperature of 10° C.

To control grape berry moth some grape growers have traditionally made two to four applications of insecticides per year on a calendar directive or on the basis of vine phenology. However, this practice has resulted in insecticide application to many vineyards where there is little threat of grape berry moth damage (Hoffman et al. 1992). Grape berry moth infestation levels can vary dramatically from year to year and from vineyard to vineyard (Danko and Jubb 1983). For example, in any given year, as much as 60% of the vineyard acreage in New York does not warrant insecticide treatment to maintain grape berry moth levels at harvest below the industry-stipulated threshold of 2% damaged berries (Hoffmann and Dennehy 1989). Basing control decisions on sample estimates of grape berry moth damage or on indirect estimators of the density of this pest, such as pheromone trap captures, sprays may be reduced. In addition, the timing of insecticide treatments and increasing precision of specific sampling periods of grape berry moth could be improved to provide a more detailed understanding of grape berry moth phenology.

Models that predict insect development use information based on degree-days and operate under the assumption that developmental time is directly related to temperatures. Also, development only occurs when temperatures exceed a specified threshold or base temperature. Determining degree-days needed for development can be accomplished using various methods. The first method uses average daily temperature (max + min/2) minus the developmental threshold to calculate degree-days. Computer programs can also be used to calculate degree-days, using a variety of waveform or sine modification methods. Regardless of the model or method used in calculating degree-days, it is important to determine when to start the degree-day accumulation (Grantham et al. 2002).

The objective of this study was to evaluate models used in the field by comparing observed dates of economic importance to predicted dates of economic importance, the latter being derived from the models.

Methods and Materials

A two year study, evaluating the efficacy of predictive models in assessing the phenology of the grape berry moth in Oklahoma, was conducted. The following locations in Oklahoma were used in evaluating the efficacy of these models for predicting phenological events: Perkins Research Station, Perkins; Tres Suenos Vineyard, Luther; and Stone Bluff Vineyard, Stone Bluff. Figure 1 provides a map of the monitoring locations across the state covered in this study.

Currently, calculation and accumulation of degree-days beginning after establishment of a bio-fix (first capture) is used to determine several expected biological events of the grape berry moth life cycle from egg to adult. In Oklahoma, the degree-day

monitoring tool for grape berry moth uses species-specific pheromone trapping techniques and is initiated after a bio-fix (first capture). Pherocon 1C traps with rubber septa lures, containing a blend of (Z)-9-dodecenyl acetate and (Z)-11-tetradecynl acetate (Trece Incorporated, Salinas, CA) were used.

Following recommendations from the University of Arkansas Cooperative Extension Services (D. Johnson – personal communication), monitoring for the grape berry moth began on April 1. Three pheromone traps per vineyard at heights of 7' to 8' were set along the edge of the woods directly adjacent to the vineyard. Traps were checked for moth captures twice weekly. After first capture a bio-fix (date of first capture) was established and the accumulation of degree-days began. Newly formed buds were also inspected along the edge row for presence of eggs.

By mid May, all traps were moved to the vineyard center (top wire) and trap inspections continued twice weekly due to emigration of grape berry moths throughout the vineyard. During May (after accumulation of 400 DD), weekly scouting for 1st generation larvae and webbing on 10 clusters on each of 10 vines along the vineyard perimeter was performed. After accumulation of 1200 DD, 50 clusters were examined in the row adjacent to the woodlot, and 50 clusters in the 10th row into the vineyard for presence of webbing and/or larvae of the second-generation of grape berry moth.

The value of predictive modeling for grape berry moth damage at harvest was evaluated for three vineyards in Oklahoma. This was accomplished by comparing predicted timing of adult moth emergence; 2nd generation larvae; 2nd generation moth mating flights and 3rd generation larvae generated by the various models to actual observed biological events.

Currently, in Oklahoma and surrounding states, the grape berry moth predictive model is initiated after a bio-fix is established. The model is then used in combination with a thermal requirement regimen equaling 400 DD accumulation for first generation larvae and 1200 DD accumulation for second generation larvae. This study evaluated accumulation of degree-days which began on calendar dates, such as; January 1, February 1, March1, April 1 and a developmental threshold model (threshold model). These 5 models were used in combination with thermal requirements established by Tobin et al. 2002 and Luciani 1987 (Table 1), as alternative methods of accumulating degree-days for use in the southern plains states. The bio-fix models' thermal requirements did not include event dates for adult emergence from overwintering pupae, completion of oviposition by overwintering generation, or completion of oviposition by first generation. Thermal requirements established by Tobin et al. 2002 and Luciani 1987 were used in combination with the bio-fix model to determine its accuracy for these events.

Temperature data for evaluating these models was supplied by the Oklahoma Mesonet system. The mesonet is one of the most sophisticated mesoscale systems in the United States (Crawford et al. 1992, Brock et al. 1995). The system consists of 114 automated data loggers with an average spacing of 19 miles linked via radio signal to the nearest Oklahoma Law Enforcement Telecommunications System station and to the Oklahoma Climatological Survey Computer in Norman, Oklahoma. Temperature readings are taken at 5-min intervals and relayed every 15 min, allowing the system to present "real-time" conditions across the state (Grantham et al. 2002). The various models were evaluated using the data supplied by the Mesonet sites nearest the vineyard

where data were gathered. The Mesonet sites included Chandler, Haskell, and Perkins, Oklahoma.

To evaluate the efficacy of the various models, actual events such as, significant damage (%) by larvae to buds, flowering, and fruiting structures, larval captures, and adult male captures, were recorded during field observations. Larval damage was determined by examining grape clusters for eggs, webbing and presence of larvae of grape berry moths. Eggs were laid singly on buds, stems, or newly formed berries. Later in the season, most eggs were laid directly on berries.

To characterize temporal patterns of grape berry moth egg depositions, 10 random samples of grape clusters were removed weekly from vines of various cultivars at three different locations. Egg sampling began in April after first capture of male grape berry moth in pheromone traps. Sampled grape clusters were transported back to the laboratory and inspected for eggs using a binocular microscope; the number of un-hatched, healthy eggs was recorded. Cultivated grapes were used because wild grapes were not found to occur in abundance around the selected vineyards in Oklahoma. Wild grapes have been used in other studies because grape berry moth females show a preference for oviposition in wild grape habitat. The total numbers of eggs found and larval damage to various structures of economic importance were recorded for each sample. These observations were made at the same time traps were read and immediately after the first grape berry moth was captured in a pheromone-baited flight trap.

To test the efficacy of each model, observed dates of phenological importance were compared to the generated expected dates from the various models. The models were used to predict first generation flight, second-generation larval emergence, second-

generation flight, and third-generation larval emergence. Predictions were compared to observations using a weighted least squares index (WLSI):

$$\frac{(\text{Observed date of emergence} - \text{model prediction})^2}{\text{Observed date of emergence}} = \text{WLSI}$$

In a WLSI, lower values indicate smaller deviations between observed and predicted values and hence, a better relationship (Richmond and Bacheler 1989).

Models were compared on the basis of the degree-day totals of predicted dates versus actual observed dates for; presence of grape berry moth larvae, webbing and significant damage from grape berry moth larvae. The difference in days between predicted and actual observed events was recorded as difference in days (±) between the two dates. The model having the smallest average difference and lowest error was deemed most suitable for use in Oklahoma. Voucher specimens of this study were placed in the K.C. Emerson Entomology Museum, 127 Noble Research Center, Oklahoma State University, Stillwater, Oklahoma.

Data recorded during the two year evaluation were analyzed using PC SAS Version 8.2 (2001, SAS Institute, Cary, NC). The input included the year number (year one and two of the study), the site (Payne, Oklahoma, or Wagoner county), the model used for prediction (bio-fix driven, calendar models-Jan.1, Feb. 1, March 1, April 1 starting dates, and a model driven by the first break of the developmental threshold), and the key phenological events of the grape berry moth (adult emergence, completion of oviposition by first generation, emergence of second generation, completion of oviposition by second generation, emergence of third generation, and completion of oviposition by third generation).

Data were analyzed using the PROC GLM and PROC MIXED procedures to detect significant differences among models in predicting each separate phenological event. If a significant difference among models was found, a Least Significant Difference (LSD) procedure was performed to determine where differences occurred.

Results

In Oklahoma County, in 2002, 108 adult male moths were captured (Figure 2). Male moths emerging from the overwintering generation occurred from April 3 to April 24. Fifty-percent and 90% of this flight of adult males were captured by April 8 and April 15, respectively. May 3 marked the first evidence of larval presence and this activity continued through May 9. Moth activity resumed May 13, with 50% and 90% of the first generation captured by May 15 and May 22, respectively. The second increase in larval activity in the field occurred on June 3 and lasted through June 5. Trap captures increased again beginning June 5. Fifty percent of adult males of second generation were captured by June 7. Ninety percent of adult males were captured by June 11. No larval activity was recorded after this date.

In Wagoner County, 141 male moths were captured (Figure 3). Male moths emerging from the overwintering generation occurred from April 3 to April 26. Fifty percent and 90% of the moths from the overwintering generation were captured by April 8 and April 22, respectively. May 3 marked the first occurence of larval populations and this activity continued through May 9. Male moth activity resumed May 13, with 50% and 90% of the first generation captured by May 15 and May 28, respectively. The second appearance of larval activity in the field occurred June 5 and lasted through June 11. Trap captures increased again beginning June 7. Fifty percent of adult males from

the second generation were captured by June 11. Ninety percent of adult males were captured by June 21. No larval activity was recorded after this date.

In Payne County, a total of 114 male moths were captured (Figure 4). Male moths emerging from the overwintering generation occurred from April 3 to April 29. Fifty percent and 90% of these moths were captured by April 10 and April 22, respectively. First appearance of larval activity was recorded on May 6 and continued through May 15. Moth activity resumed May 13, with 50% and 90% of the first generation captured by May 17 and June 3, respectively. The second occurrence of larval activity in the field began on June 7 and was recorded through June 9. Trap captures increased again beginning June 7. Fifty percent of adult males from the second generation were captured by June 14. Ninety percent of adult males were captured by June 25. No larval activity was recorded after this date.

The second year of this study resumed in early spring of 2003. In Oklahoma County, a total of 226 male grape berry moths were captured (Figure 5). Male moths emerging from the overwintering generation occurred from April 4 to April 22. Fifty percent and 90% of these moths were captured by April 4 and April 18, respectively. First appearance of larval activity was recorded on May 2 and continued through May 9. Male moth activity resumed May 9, with 50% and 90% of the total captures reached by May 13 and May 27, respectively. The second occurence of larval activity took place June 6 in the field, and lasted through June 13. No grape berry moth activity was recorded after this date.

In Wagoner County, 241 male moths were captured (Figure 6). Male moths emerging from the overwintering generation were detected from April 1 to April 18.

Fifty percent and 90% of the total captures from this flight were recorded by April 4 and April 15, respectively. Initial larval activity began May 6 and continued through May 16. Male moth activity resumed May 13, with 50% and 90% of the first generation captured on May 16 and May 30, respectively. Second occurrence of larval activity in the field began June 10 and lasted through June 13. Adult trap captures increased again beginning June 13 with 50% and 90% of the second generation captured recorded on June 17 and June 24, respectively. No grape berry moth activity was recorded after this date.

In Payne County, a total of 151 male moths were captured (Figure 7). Male moths emerging from the overwintering generation were detected from April 4 to April 11. Fifty percent and 90% of the total captures from this initial flight were recorded by April 4 and April 8, respectively. First occurrence of larval activity began May 6 and continued through May 13. Male moth activity resumed May 13, with 50% and 90% of the total captures of the first generation recorded by May 20 and May 27, respectively. Second occurrence of larval activity in the field began June 3 and lasted through June 10. No larval grape berry moth activity was recorded after this date.

Results in testing the efficacy of predictive models using the WLSI revealed a strong relationship (a small WLSI value) between observed and predicted events using a Jan. 1 model (Figure 8) and a Feb. 1 model (Figure 9) for 2002. All three test sites (Perkins, Luther and Stone Bluff [SB], Ok) and the economically important stages (1^{st} and 2^{nd} generation larvae) are represented in these figures. In 2003, results testing the efficacy of predictive models using the WLSI for economically important stages also showed a strong relationship (a small WLSI value) between observed and predicted events using a Jan. 1 model (Figure 10), or a Feb. 1 model (Figure 11). All three test

sites, each economically important stage (1st and 2nd generation larvae) and each year are represented in Figures 8-11. These models were particularly accurate at predicting the economically important stages (1st and 2nd generation larvae) for both years of the study. In addition, both models were early in predicting the economically important stages, which is critical when trying to anticipate application of control measures.

The bio-fix driven model (Figure 12), March 1 model (Figure 13) and the April 1 model (Figure 14) displayed a less accurate relationship between observed and predicted dates for 2002. In addition, these latter three models were all late in predicting the occurrence of 1st generation larvae at all three test sites (Figures 12-14). In 2003, the bio-fix model (Figure 15) was late in predicting 1st and 2nd generation larvae at two of the three test sites (Luther and Stone Bluff [SB], Ok). Likewise, in 2003, the March 1 model (Figure 16) was late in predicting 2nd generation larvae at two of the three test sites (Luther and Stone Bluff [SB], Ok). Similarly, in 2003, the April 1 model (Figure 17) was late in predicting 1st and 2nd generation larvae at two of the three test sites (Luther and Stone Bluff [SB], Ok). An appendix displaying all WLSI values is attached (Appendix 1).

Data pertaining to the various models and their predictive value in anticipating phenological events were analyzed to determine which model predicted adult emergence from overwintering pupae (event 1) most accurately. The GLM procedure calculated a significant difference ($F=279.4$, $df=5$, $P<.0001$) among the models (Table 2). The model initiated on Jan.1 (mean=±3.333 days from actual event) and at developmental threshold (threshold model) (mean=±3.667 days from actual event) were not significantly different from one another, but were significantly different from models initiated on the bio-fix

(mean=±21 days from actual event), Feb. 1 (mean=±6.8 days from actual event), March 1 (mean=±11.1667 days from actual event), and April 1 (mean=±21.67 days from event). The bio-fix and April 1 models were not significantly different from one another, but were significantly different from the other models.

The second analysis sought to determine which model predicted most accurately the completion of oviposition by moths of the overwintering generation (event 2). The GLM procedure calculated a significant difference ($F=25.6$, $df=5$, $P<.0001$) among the models (Table 3). The models initiated on Jan.1 (mean=±3.167 days from actual event) and at developmental threshold (threshold model) (mean=±3.333 days from actual event) were not significantly different from one another, but were significantly different from those models initiated at the bio-fix (mean=±16.667 days from actual event), Feb. 1 (mean=±7.167 days from actual event), March 1 (mean=±11.5 days from actual event), and April 1(mean=±15.5 days from event). The bio-fix and April 1 models were not significantly different from one another, but were significantly different from the other models.

The third analysis was conducted to determine which model predicted most accurately the emergence of the first complete generation (event 3). The GLM procedure calculated a significant difference ($F=78.67$, $df=5$, $P<.0001$) among the models (Table 4). Models initiated on Jan.1 (mean=±2.667 days from actual event) and at developmental threshold (threshold model) (mean=±3.5 days from actual event) were not significantly different from one another, but were significantly different from models derived from the bio-fix (mean=±20.667 days from actual event), Feb. 1 (mean=±8.00 days from actual event), March 1 (mean=±9.833 days from actual event), and April 1

(mean=±19.5 days from event). The bio-fix and April 1 models were not significantly different from one another, but were significantly different from the other models. The March 1 and Feb 1 models were not significantly different from one another, but were significantly different from the other models.

The fourth analysis was conducted to determine which model predicted most accurately the completion of oviposition by first generation moths (event 4). The GLM procedure calculated a significant difference ($F=33.28$, $df=5$, $P<.0001$) among the models (Table 5). Models initiated on Jan.1 (mean=±3.166 days from actual event) and at developmental threshold (threshold model) (mean=±4.333 days from actual event) were not significantly different from one another, but were significantly different from models generated at the bio-fix (mean=±12.166 days from actual event), Feb. 1 (mean=±7.333 days from actual event), March 1 (mean=±9.5 days from actual event), and April 1 (mean=±12.666 days from event). The bio-fix and April 1 models were not significantly different from one another, but were significantly different from the other models.

The fifth analysis was conducted to determine which model predicted most accurately the emergence of second generation (event 5). The GLM procedure calculated a significant difference ($F=13.37$, $df=5$, $P<.0004$) among the models (Table 6). Models initiated on Jan.1 (mean=±2.5 days from actual event) and at developmental threshold (threshold model) (mean=±3.333 days from actual event) were not significantly different from one another, but were significantly different from those generated on the bio-fix (mean=±12.83 days from actual event), Feb. 1 (mean=±6.833 days from actual event), March 1 (mean=±9.667 days from actual event), and April 1 (mean=±11.167 days from

event). The threshold model was not significantly different from the Feb. 1 model. The Feb. 1 model was not significantly different from the threshold or the March 1 model. The March 1 model was not significantly different from the Feb.1, April 1, or bio-fix models. The April 1 model was not significantly different from the bio-fix model or the March 1 model, but was significantly different from the other models. The bio-fix model was not significantly different from the April 1 model, but was significantly different from the remaining models.

Finally, data were analyzed to determine which model predicted most accurately the completion of oviposition by second-generation moths (event 6). The GLM procedure calculated a significant difference ($F=26.83$, $df=5$, $P<.0001$) among the models (Table 7). Models initiated on Jan.1 (mean=±3.5 days from actual event) and at developmental threshold (threshold model) (mean=±5.166 days from actual event) were not significantly different from one another. The Jan.1 model was significantly different from the other models. The model initiated at developmental threshold was not significantly different from the Feb. 1 model (mean±6.5 days from actual event), but was significantly different from models generated at the bio-fix (mean±10.833 days from actual event), March 1 (mean±11.667 days from the actual event) and April 1 (mean±11.8333 days from the actual event). The Feb. 1 model was significantly different from the Jan.1 model, the bio-fix model, the March 1 model and the April 1 model, but was not significantly different from the threshold model. The bio-fix model was significantly different from the Feb. 1, threshold, and Jan. 1 models, but not the March 1 and April 1 models. The March 1 model was significantly different from the Feb. 1, threshold, and Jan. 1 models, but not the bio-fix or April 1 models. The April 1 model

was significantly different from the Feb. 1, threshold, and Jan. 1 models, but not the March 1 and bio-fix models. The PROC MIXED procedure was conducted to further confirm the analysis. No differences were found in the two types of analyses.

Discussion

Grape production in Oklahoma has the potential to become a solid market for the state. The variety selected by the producer and management practices will have a major impact on this assessment. This two year study suggests that grape berry moth could be the major pest on grapes in Oklahoma during any given year. Trap captures, in combination with a highly wooded landscape, display enough evidence to merit such a statement. The fact that Oklahoma is heavily wooded in many areas of the state (Northeast) may lead to growth in production of grapes in western locations. Grape berry moth appears to be bi or tri-voltine in Oklahoma, depending on location of the vineyard. It should also be noted that 2nd generation larvae will impose the most economic damage from year to year, based on the correlation of fruit maturity and larval appearance. However, larvae seem to be non-discriminatory when feeding, all potential feeding sites were fed upon (buds, flowering structures, and fruit). Vineyards with the heaviest vegetative growth appeared to be the most problematic for grape berry moth larval infestations. This is expected since older vineyards produce more vegetative growth. Grape berry moth populations have more time to establish in aged vineyards.

It would be valid to suggest the initiation of degree-day accumulation based on a January 1or developmental temperature threshold to predict the life stages of grape berry moth in Oklahoma. After accumulation of 190 Degree-days, pheromone traps should be placed in the surrounding wooded areas and monitoring for adult grape berry moth

captures should begin. The January 1 and developmental threshold models are particularly accurate in predicting the economically important stages of grape berry moth (1^{st} and 2^{nd} generation larvae). It would be a sound practice to begin scouting for eggs shortly after first capture, when grape berry moths are attracted to pheromone traps they are seeking mates. However, it is not necessary to scout for eggs shortly after first capture if buds or fruits are not present. In addition, these models predict the occurrence of economically important stages prior to their arrival. This is beneficial because producers want to be able to anticipate and prevent damage before it occurs. Using the current bio-fix model, producers are initiating scouting practices late, resulting in unnecessary damage done to grapes and the likelihood of increased insecticide sprays. It is understandable that the bio-fix model does not predict emergence from overwintering pupae accurately, the model was not designed to predict this stage.

It should be noted that life stages that occur late in the season become harder to predict. However, models initiated on Jan. 1 and at developmental threshold are significantly better at predicting the occurrence of all stages. It is suspected that the significant difference in years (2002 and 2003) for events 5 and 6 are directly related to the fact that these stages occur late in the season. Furthermore, we suggest that the decrease in larval activity of grape berry moth at all three sites was directly related to control measures (insecticide applications) used by the producers.

To verify the presence of grape berry moth in vineyards a rapid incubation procedure was developed in the laboratory. Digital images were taken (Figure 18) to document this procedure and could warrant subsequent studies for development of an additional IPM tool for grape producers in Oklahoma. Clusters containing webbing

(Figure 18C) were selected from the grape vines and placed into 1 gallon plastic, Ziploc® bags. A damp paper towel was placed in the bag along with the cluster. The incubation bag was then placed within another 1 gallon bag and sealed. If the webbing belonged to the grape berry moth, larvae (Figure 18B) pupated into adults (Figure 18F) within 3 days. Observations of larvae crawling from clusters and cutting pupation chambers (Figure 18D and E) in the incubation bag (Figure 18D) were consistent, and very intriguing.

Lastly, it does not appear that predictive modeling is capable of replacing common sense and good scouting practices. There are always unpredictable weather patterns in which unexpected freezes or storms can occur. These unexpected events may play a key role in determining the validity of the predicted dates of grape berry moth developmental models. Past reports on *E. viteana* seasonality indicate much variation from year to year, even within the same geographic location. For example, Hoffman et al. (1992) noted trivoltinism in New York State vineyards in 1987, but only bivoltinism the following year in the same vineyards. Several researchers have noted year-to-year variation in voltinism, from 1.5 to 3.5 generation per year (Ingerson 1920, Gleissner 1943, Luciani 1987). Future studies should continue to consider biotic factors, such as host phenology and cultivar.

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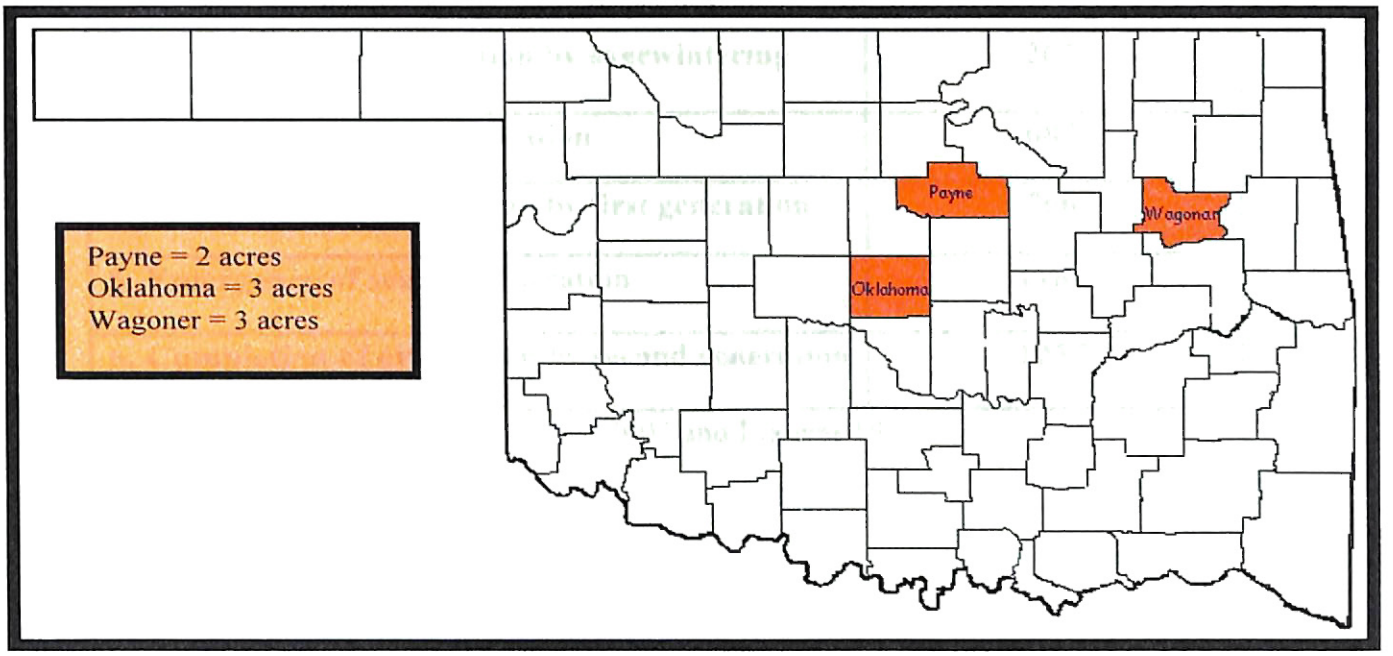
Appendix 1. Results of observed vs. expected dates Payne, Oklahoma, and Wagoner County

Location	Model-Type	Economic Stage	WLSI value
Perkins, Ok 2002	Jan. 1 Calendar Model	1st generation larvae	.031
Perkins, Ok 2002	Jan. 1 Calendar Model	2nd generation larvae	.025
Perkins, Ok 2002	Feb. 1 Calendar Model	1st generation larvae	.196
Perkins, Ok 2002	Feb. 1 Calendar Model	2nd generation larvae	.509
Perkins, Ok 2002	March 1 Calendar Model	1st generation larvae	1.54
Perkins, Ok 2002	March 1 Calendar Model	2nd generation larvae	.905
Perkins, Ok 2002	April 1 Calendar Model	1st generation larvae	3.81
Perkins, Ok 2002	April 1Calendar Model	2nd generation larvae	2.12
Perkins, Ok 2002	Bio-fix Driven Model	1st generation larvae	2.55
Perkins, Ok 2002	Bio-fix Driven Model	2nd generation larvae	3.83
Luther, Ok 2002	Jan. 1 Calendar Model	1st generation larvae	.0725
Luther, Ok 2002	Jan. 1 Calendar Model	2nd generation larvae	.0258
Luther, Ok 2002	Feb. 1 Calendar Model	1st generation larvae	.516
Luther, Ok 2002	Feb. 1 Calendar Model	2nd generation larvae	.103
Luther, Ok 2002	March 1 Calendar Model	1st generation larvae	.653
Luther, Ok 2002	March 1 Calendar Model	2nd generation larvae	.523
Luther, Ok 2002	April 1 Calendar Model	1st generation larvae	.975
Luther, Ok 2002	April 1Calendar Model	2nd generation larvae	.929
Luther, Ok 2002	Bio-fix Driven Model	1st generation larvae	1.81
Luther, Ok 2002	Bio-fix Driven Model	2nd generation larvae	1.26

Stone Bluff, Ok 2002	Jan. 1 Calendar Model	1st generation larvae	.072
Stone Bluff, Ok 2002	Jan. 1 Calendar Model	2nd generation larvae	.006
Stone Bluff, Ok 2002	Feb. 1 Calendar Model	1st generation larvae	.516
Stone Bluff, Ok 2002	Feb. 1 Calendar Model	2nd generation larvae	.229
Stone Bluff, Ok 2002	March 1 Calendar Model	1st generation larvae	1.16
Stone Bluff, Ok 2002	March 1 Calendar Model	2nd generation larvae	.77
Stone Bluff, Ok 2002	April 1 Calendar Model	1st generation larvae	1.58
Stone Bluff, Ok 2002	April 1Calendar Model	2nd generation larvae	.407
Stone Bluff, Ok 2002	Bio-fix Driven Model	1st generation larvae	1.58
Stone Bluff, Ok 2002	Bio-fix Driven Model	2nd generation larvae	.917
Perkins, Ok 2003	Jan. 1 Calendar Model	1st generation larvae	.07
Perkins, Ok 2003	Jan. 1 Calendar Model	2nd generation larvae	.058
Perkins, Ok 2003	Feb. 1 Calendar Model	1st generation larvae	.385
Perkins, Ok 2003	Feb. 1 Calendar Model	2nd generation larvae	.316
Perkins, Ok 2003	March 1 Calendar Model	1st generation larvae	.77
Perkins, Ok 2003	March 1 Calendar Model	2nd generation larvae	1.24
Perkins, Ok 2003	April 1 Calendar Model	1st generation larvae	1.32
Perkins, Ok 2003	April 1Calendar Model	2nd generation larvae	1.01
Perkins, Ok 2003	Bio-fix Driven Model	1st generation larvae	1.54
Perkins, Ok 2003	Bio-fix Driven Model	2nd generation larvae	.75
Luther, Ok 2003	Jan. 1 Calendar Model	1st generation larvae	.13
Luther, Ok 2003	Jan. 1 Calendar Model	2nd generation larvae	.101
Luther, Ok 2003	Feb. 1 Calendar Model	1st generation larvae	.398

Luther, Ok 2003	Feb. 1 Calendar Model	2nd generation larvae	.227
Luther, Ok 2003	March 1 Calendar Model	1st generation larvae	.658
Luther, Ok 2003	March 1 Calendar Model	2nd generation larvae	.632
Luther, Ok 2003	April 1 Calendar Model	1st generation larvae	1.59
Luther, Ok 2003	April 1Calendar Model	2nd generation larvae	1.06
Luther, Ok 2003	Bio-fix Driven Model	1st generation larvae	4.68
Luther, Ok 2003	Bio-fix Driven Model	2nd generation larvae	3.24
Stone Bluff, Ok 2003	Jan. 1 Calendar Model	1st generation larvae	.125
Stone Bluff, Ok 2003	Jan. 1 Calendar Model	2nd generation larvae	.055
Stone Bluff, Ok 2003	Feb. 1 Calendar Model	1st generation larvae	.503
Stone Bluff, Ok 2003	Feb. 1 Calendar Model	2nd generation larvae	.501
Stone Bluff, Ok 2003	March 1 Calendar Model	1st generation larvae	.925
Stone Bluff, Ok 2003	March 1 Calendar Model	2nd generation larvae	.501
Stone Bluff, Ok 2003	April 1 Calendar Model	1st generation larvae	1.54
Stone Bluff, Ok 2003	April 1Calendar Model	2nd generation larvae	1.20
Stone Bluff, Ok 2003	Bio-fix Driven Model	1st generation larvae	1.54
Stone Bluff, Ok 2003	Bio-fix Driven Model	2nd generation larvae	2.01

Fig. 1. Oklahoma map showing the location of the various trapping sites used for monitoring grape berry moth adult males



Payne County – Perkins Research Station
Oklahoma County – Tres Suenos Vineyard
Wagoner County – Stone Bluff Vineyard

Table 1. Predicted* cumulative degree days of *E. viteana* phenological events

Phenological Event	Cummulative Degree-Days from January 1
1. Adult emergence from overwintering pupae	190
2. Completion of oviposition by overwintering generation	263
3. Emergence of first generation	687
4. Completion of oviposition by first generation	760
5. Emergence of second generation	1184
6. Completion of oviposition by second generation	1257

*Adopted from Tobin et al. 2001, 2002 and Luciani 1987

Figure 2. Male Grape Berry Moth Flight Activity for Oklahoma County, 2002

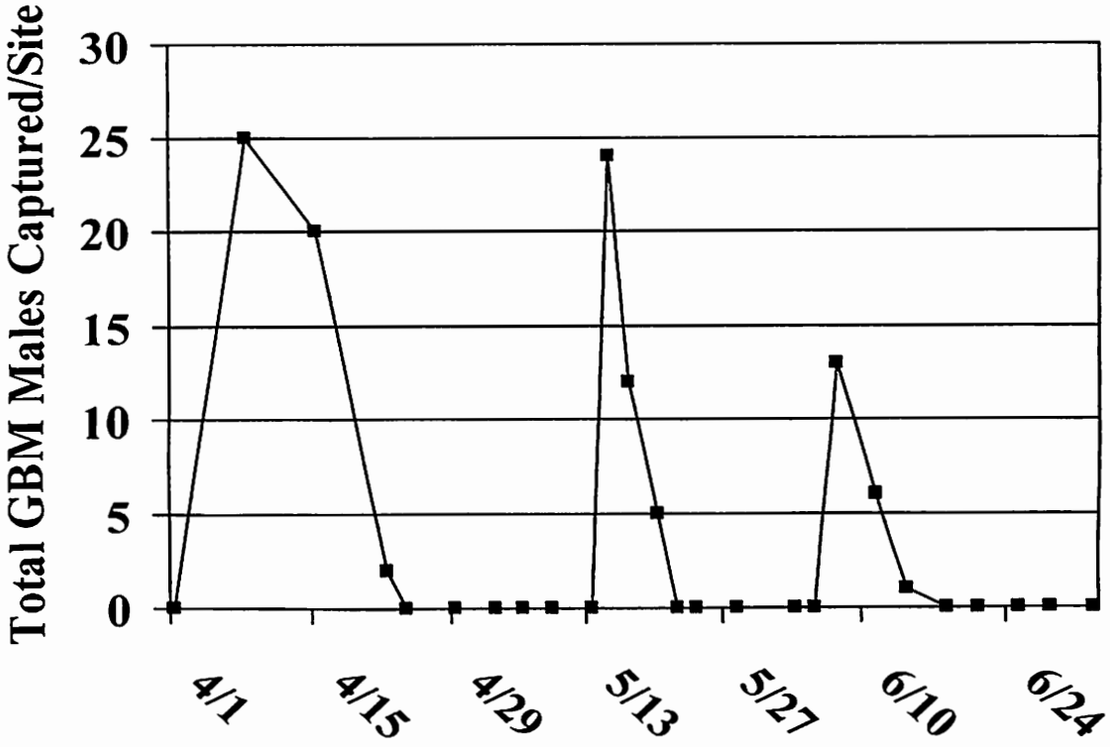


Figure 3. Male Grape Berry Moth Flight Activity for Wagoner County, 2002

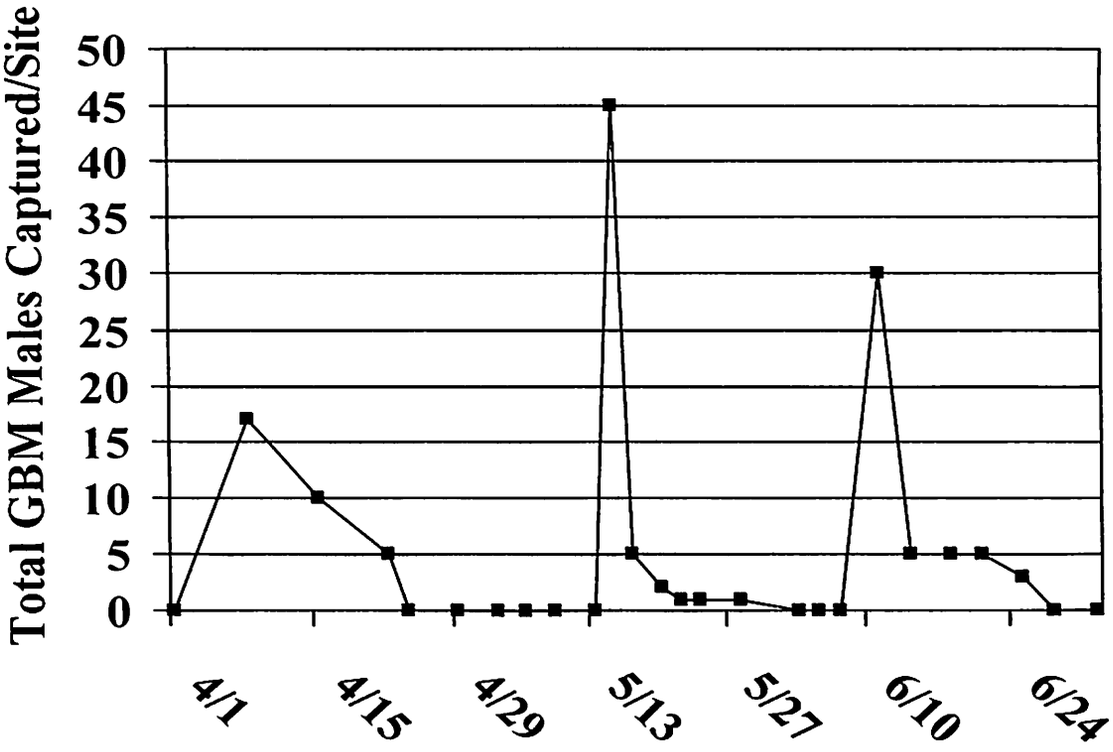


Figure 4. Male Grape Berry Moth Flight Activity for Payne County, 2002

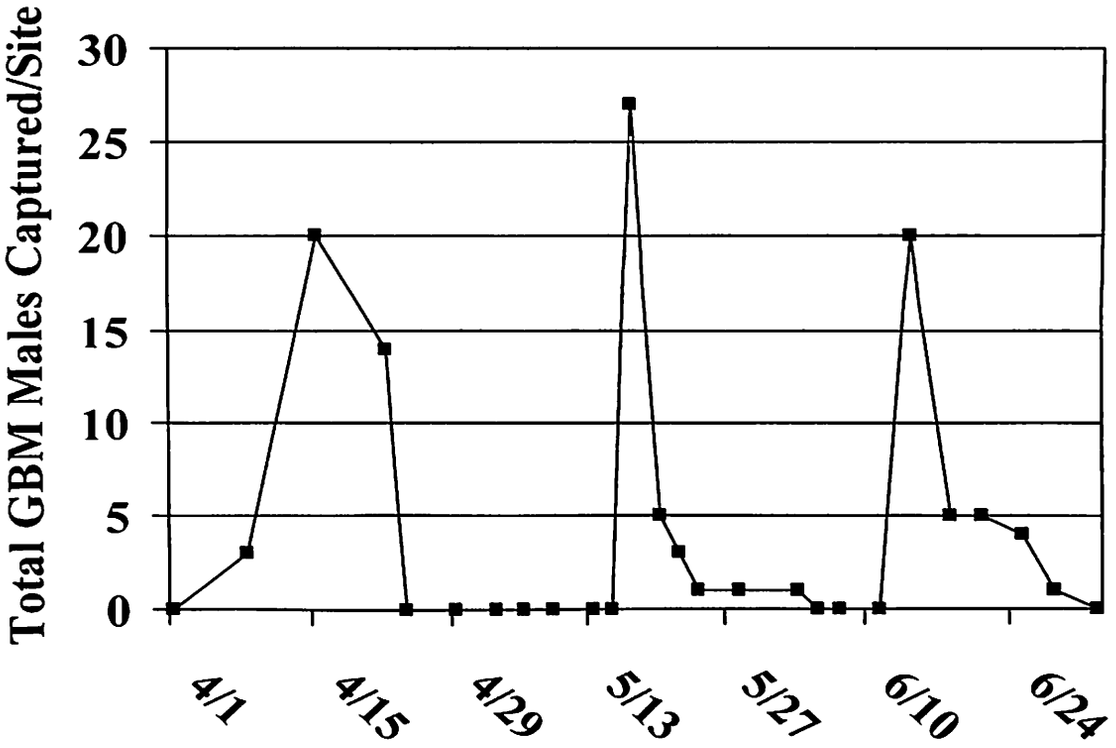


Figure 5. Male Grape Berry Moth Flight Activity for Oklahoma County, 2003

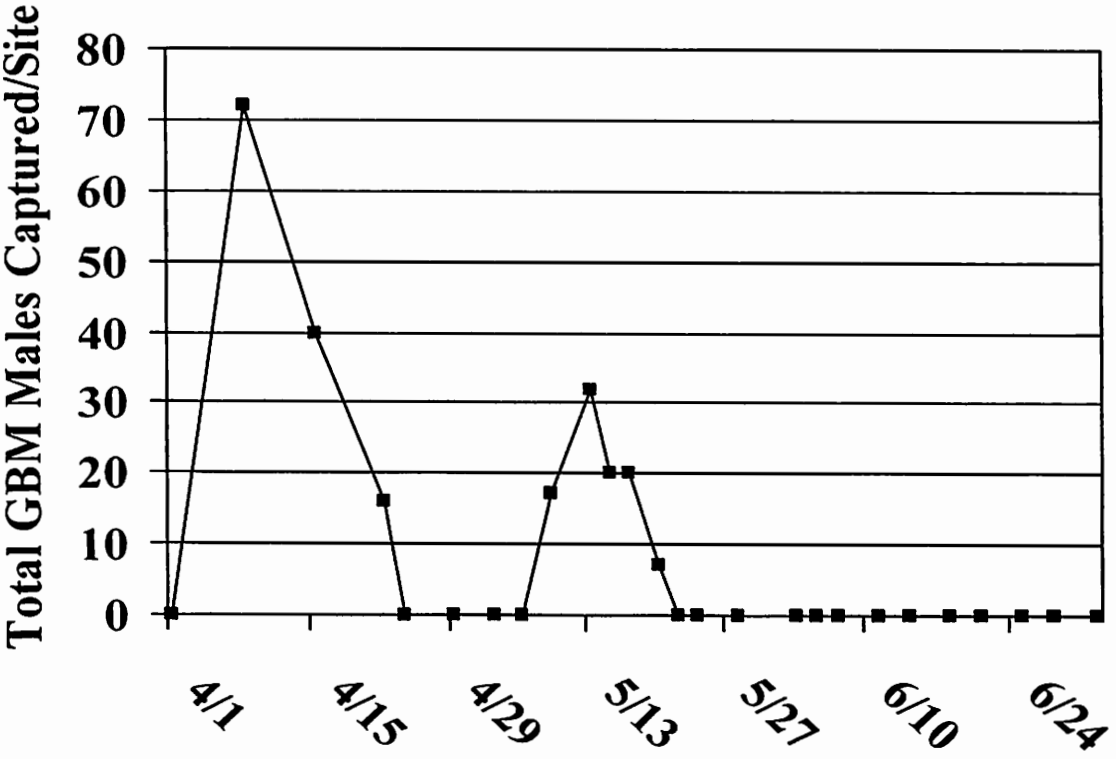


Figure 6. Male Grape Berry Moth Flight Activity for Wagoner County, 2003

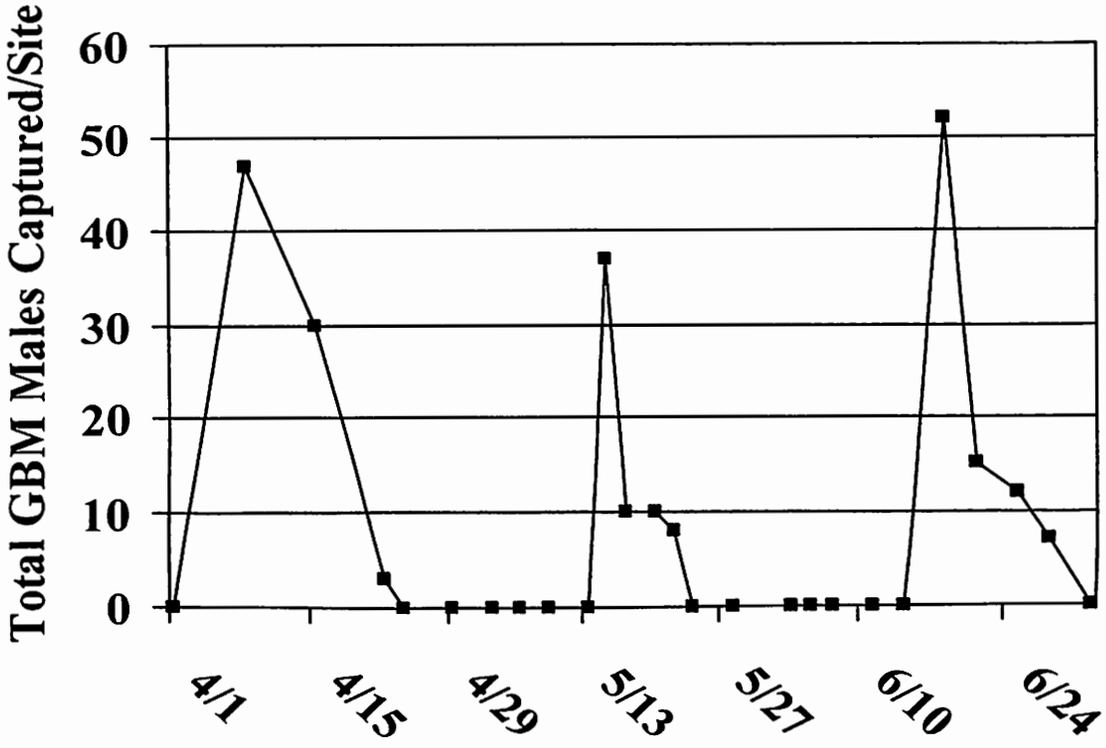


Figure 7. Male Grape Berry Moth Flight Activity for Payne County, 2003

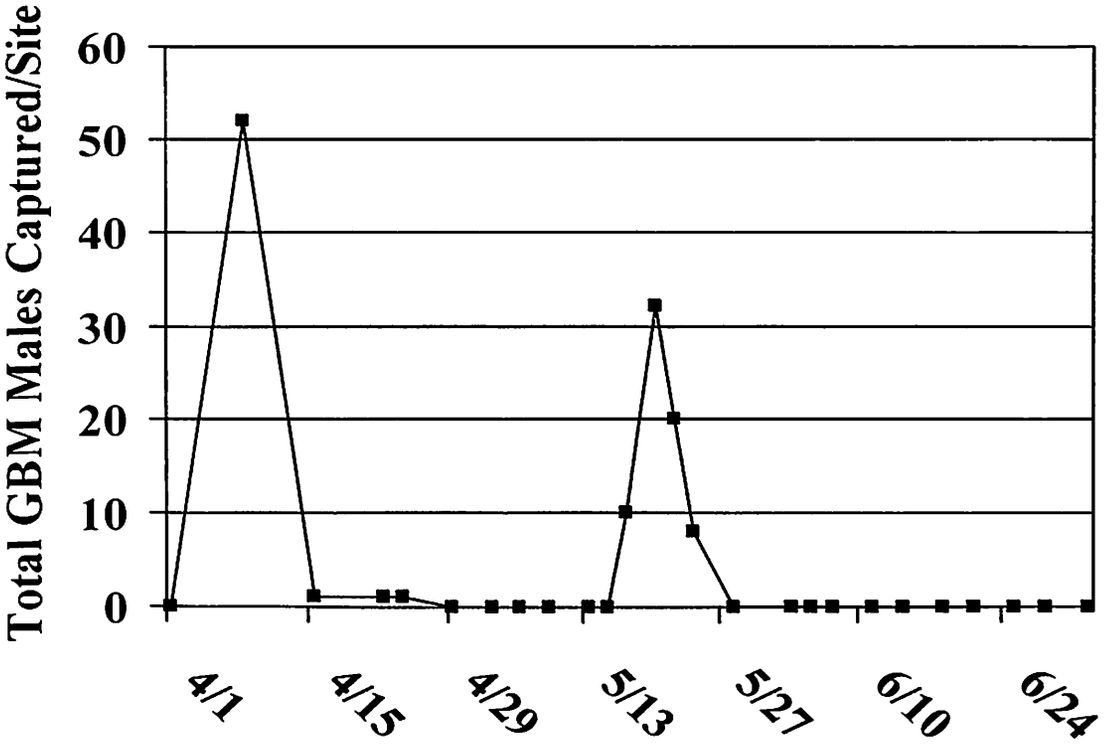


Figure 8. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the Jan. 1 model, 2002

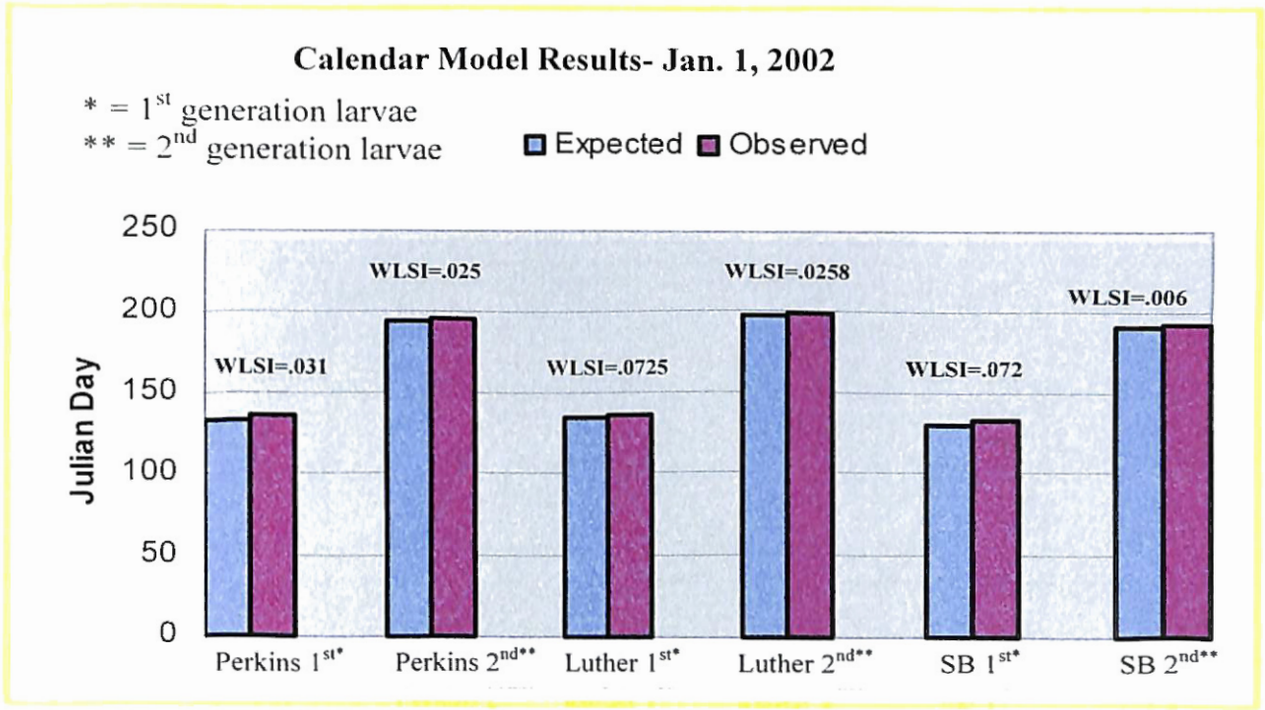


Figure 9. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the Feb. 1 model, 2002

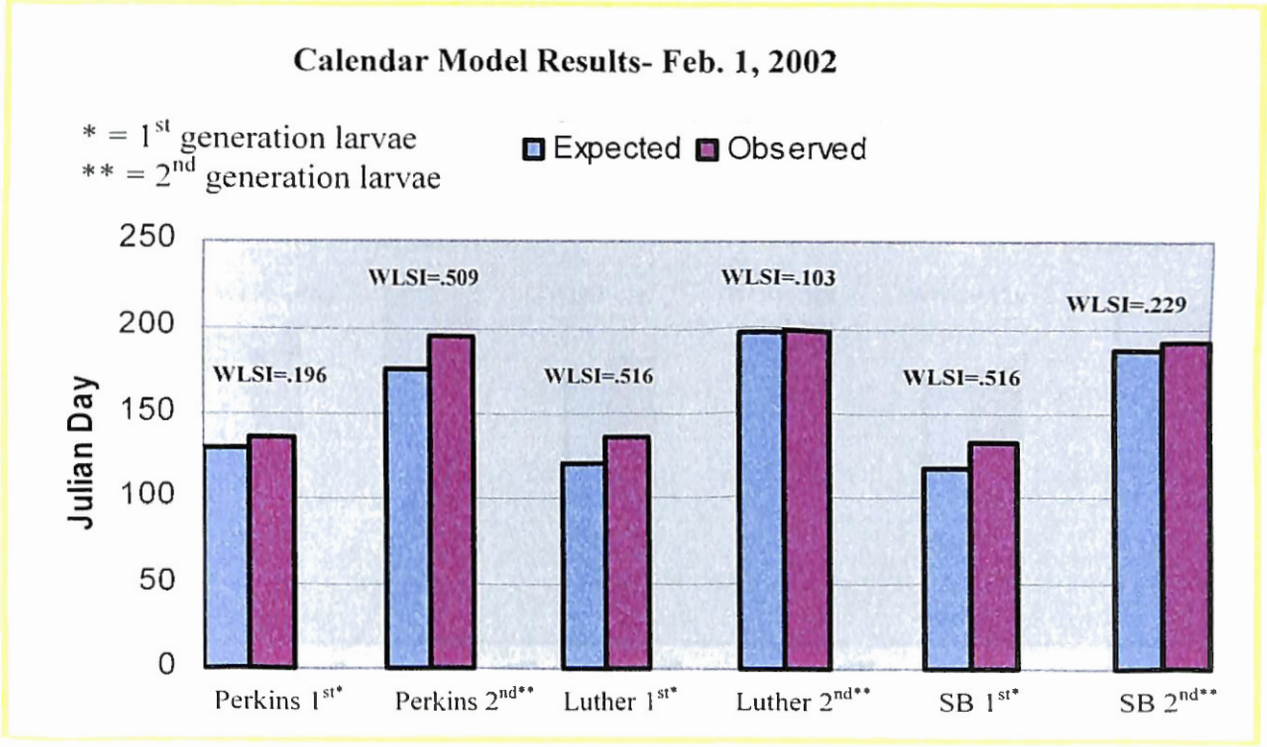


Figure 10. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the Jan. 1 model, 2003

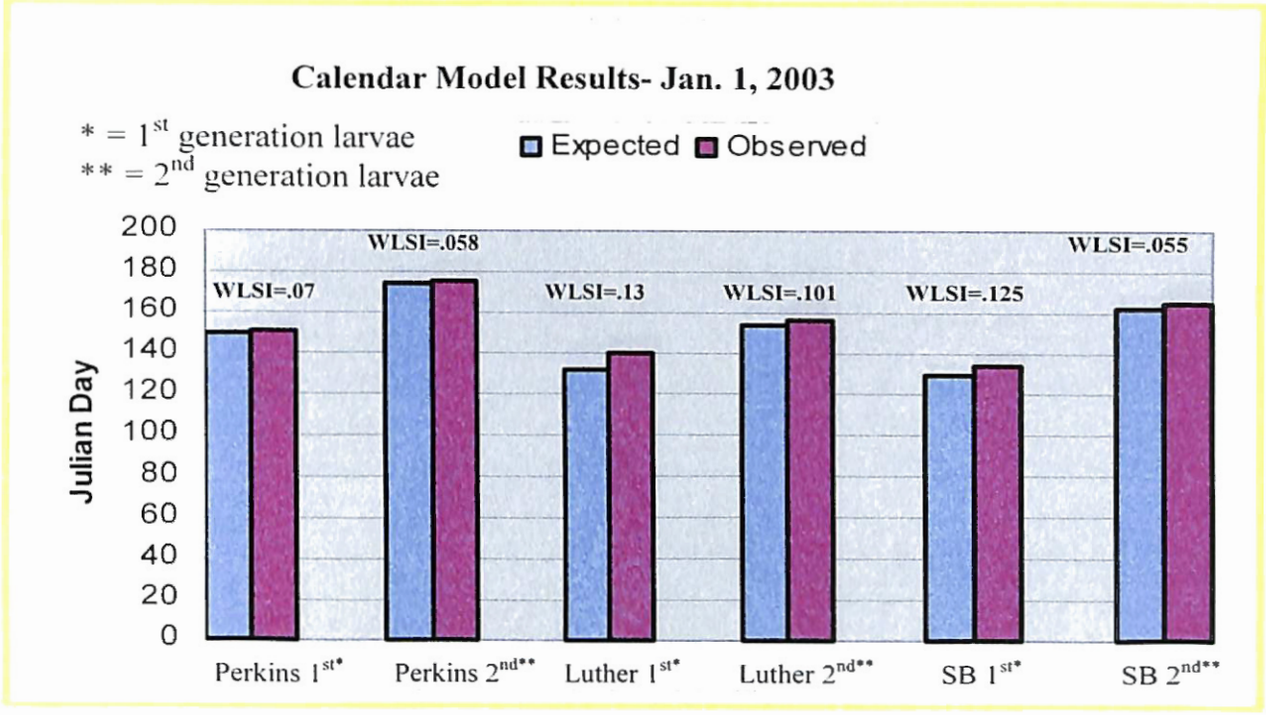


Figure 11. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the Feb. 1 model, 2003

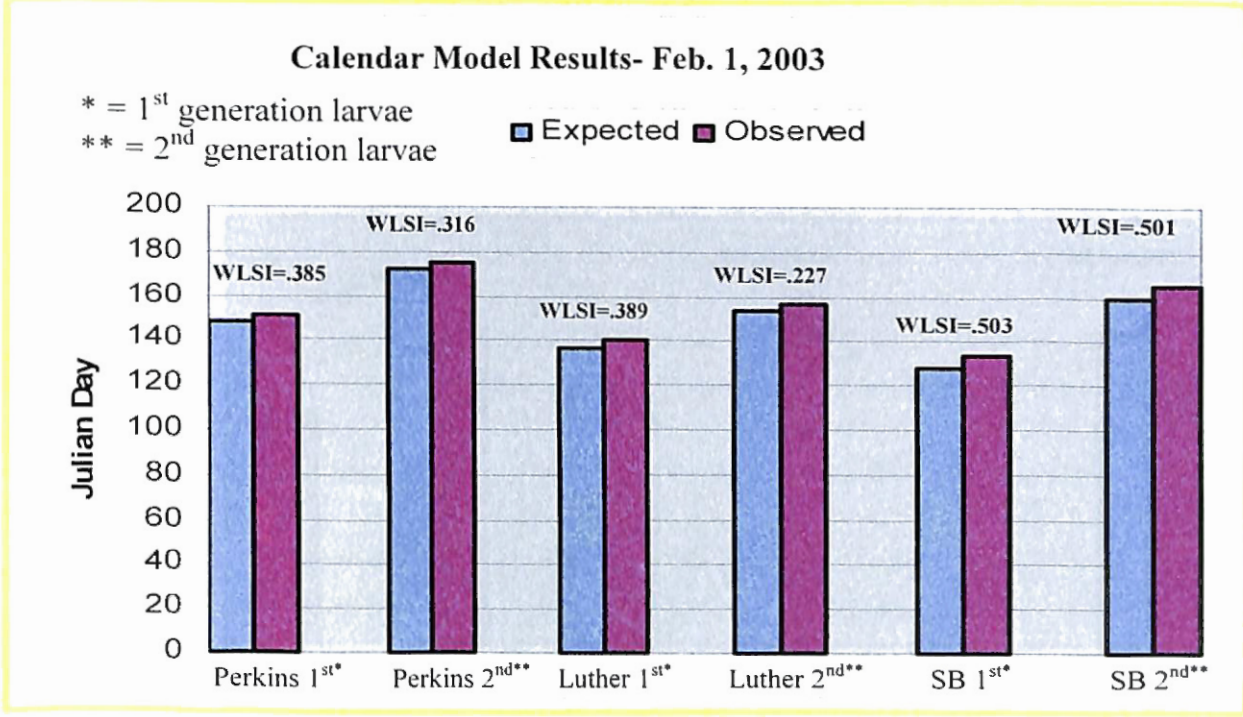


Figure 12. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the Bio-fix model, 2002

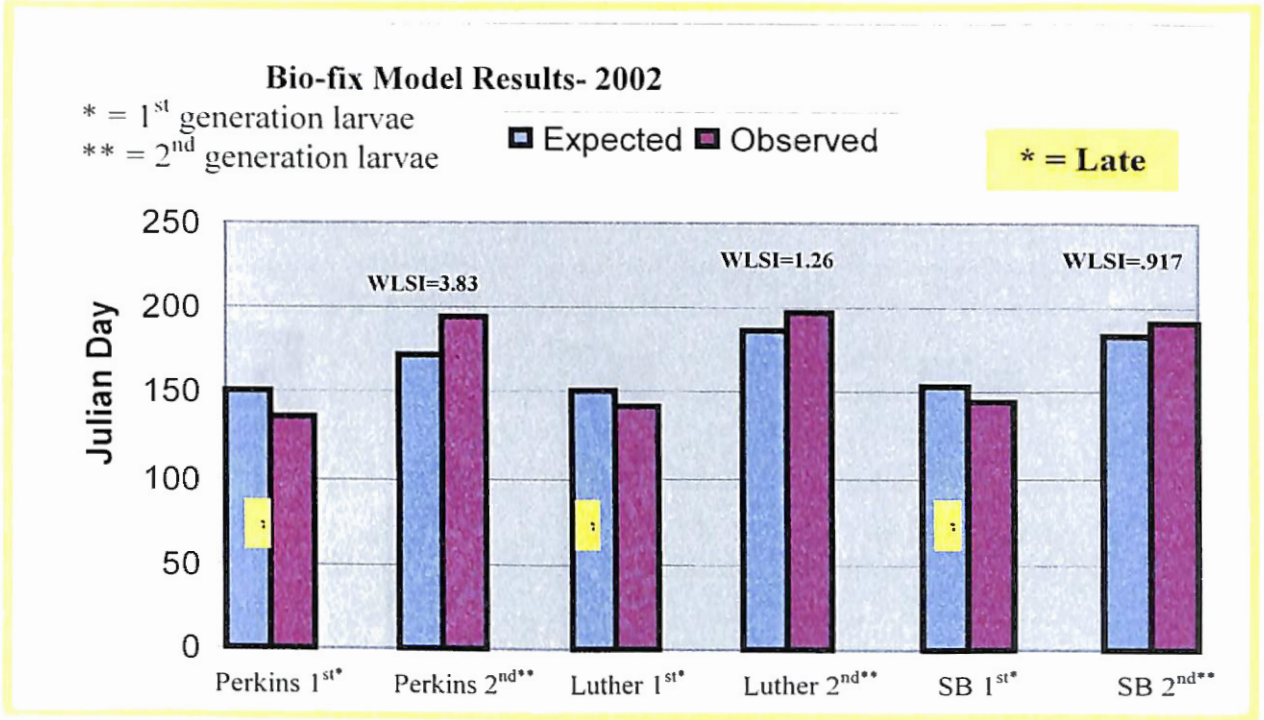


Figure 13. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the March 1 model, 2002

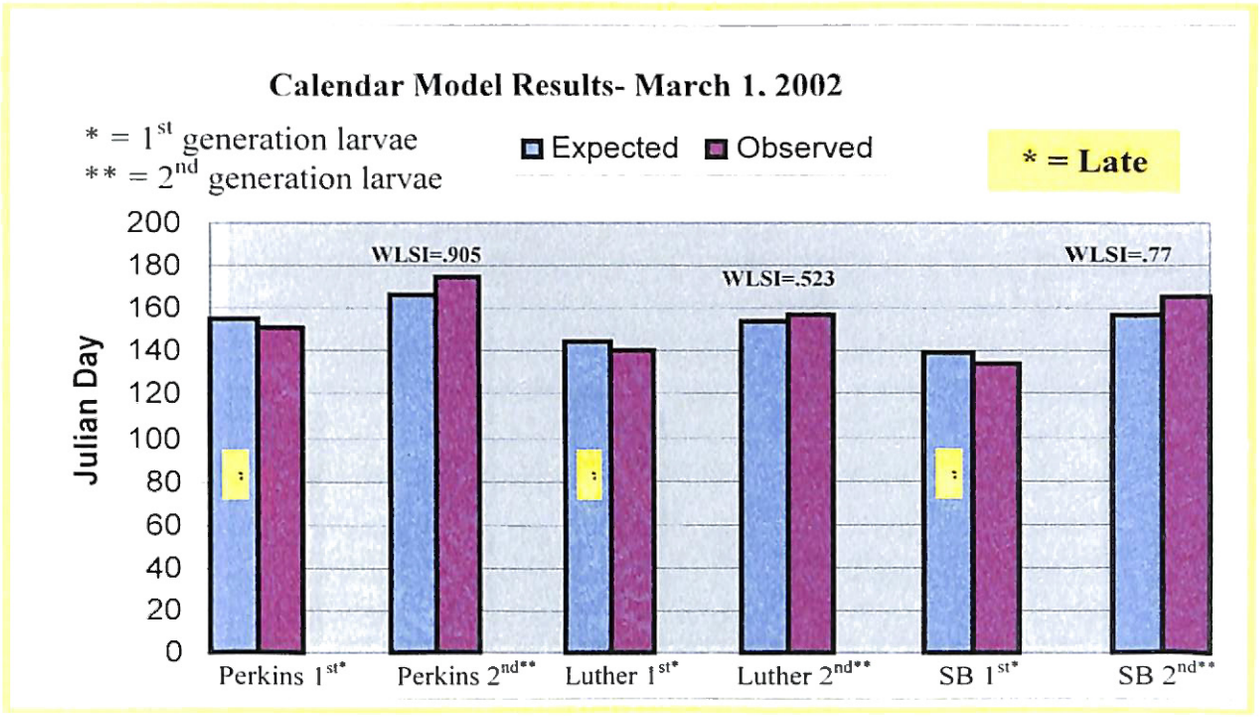


Figure 14. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the April 1 model, 2002

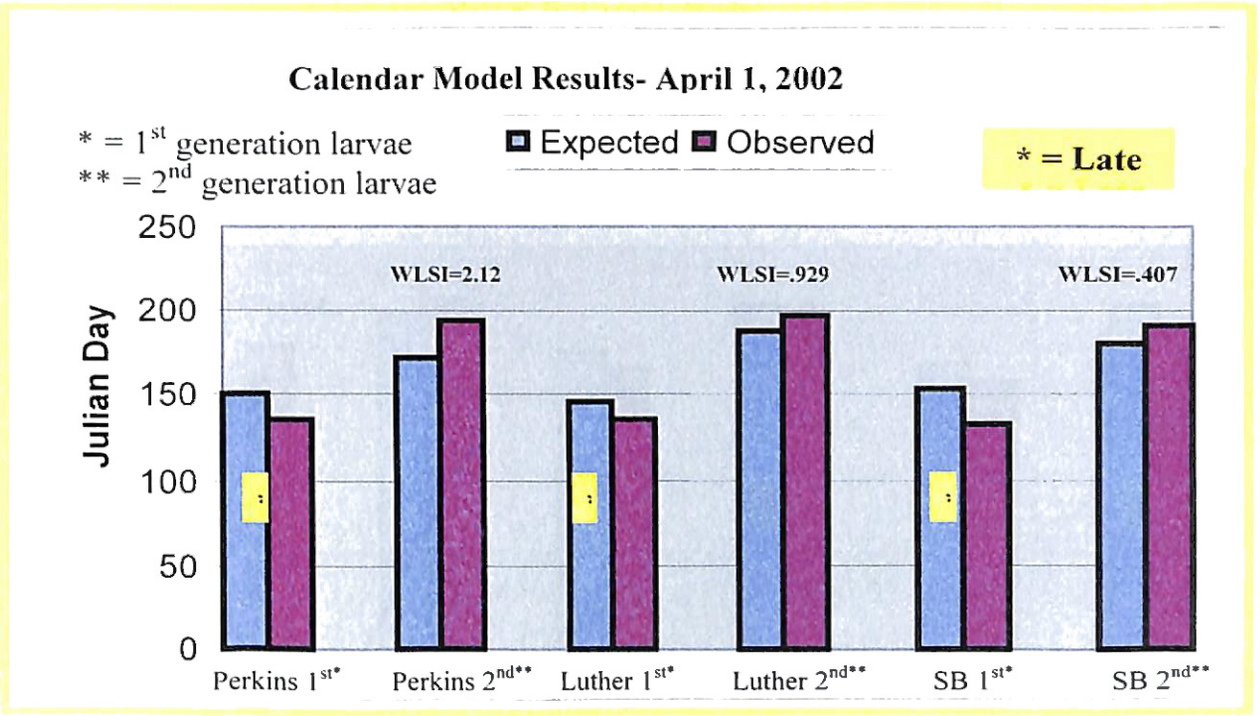


Figure 15. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the Bio-fix model, 2003

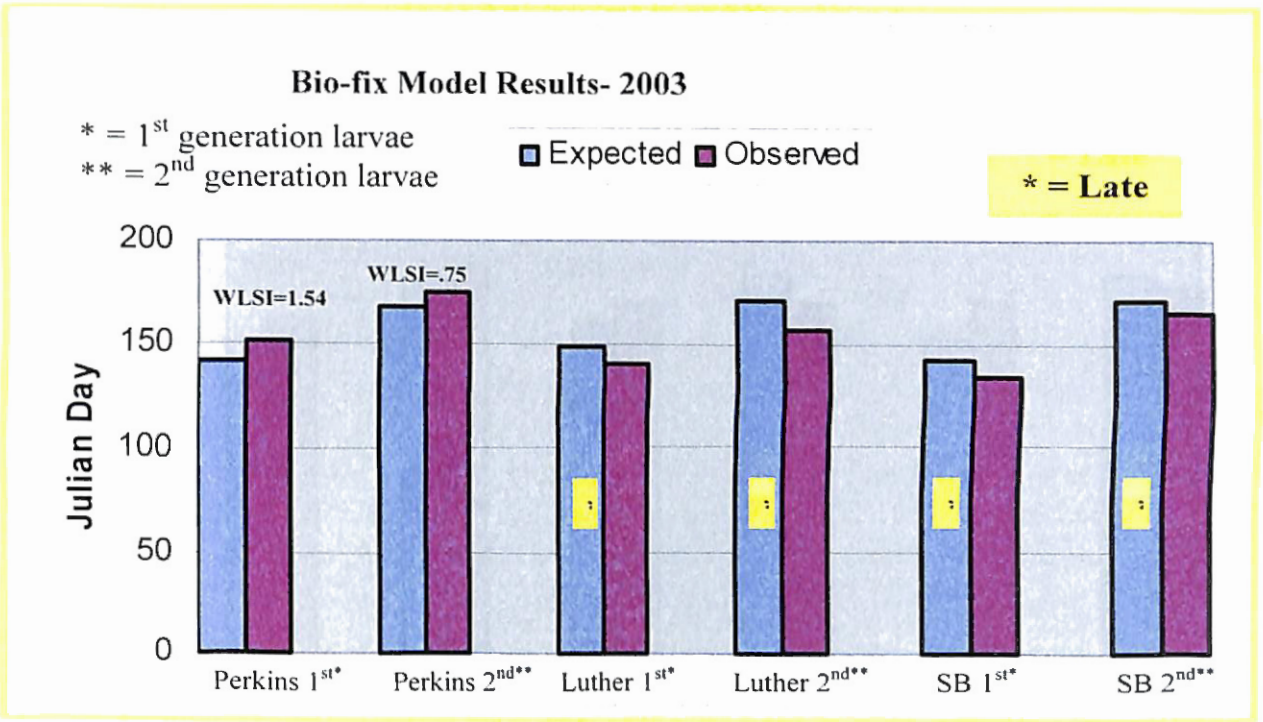


Figure 16. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the March 1 model, 2003

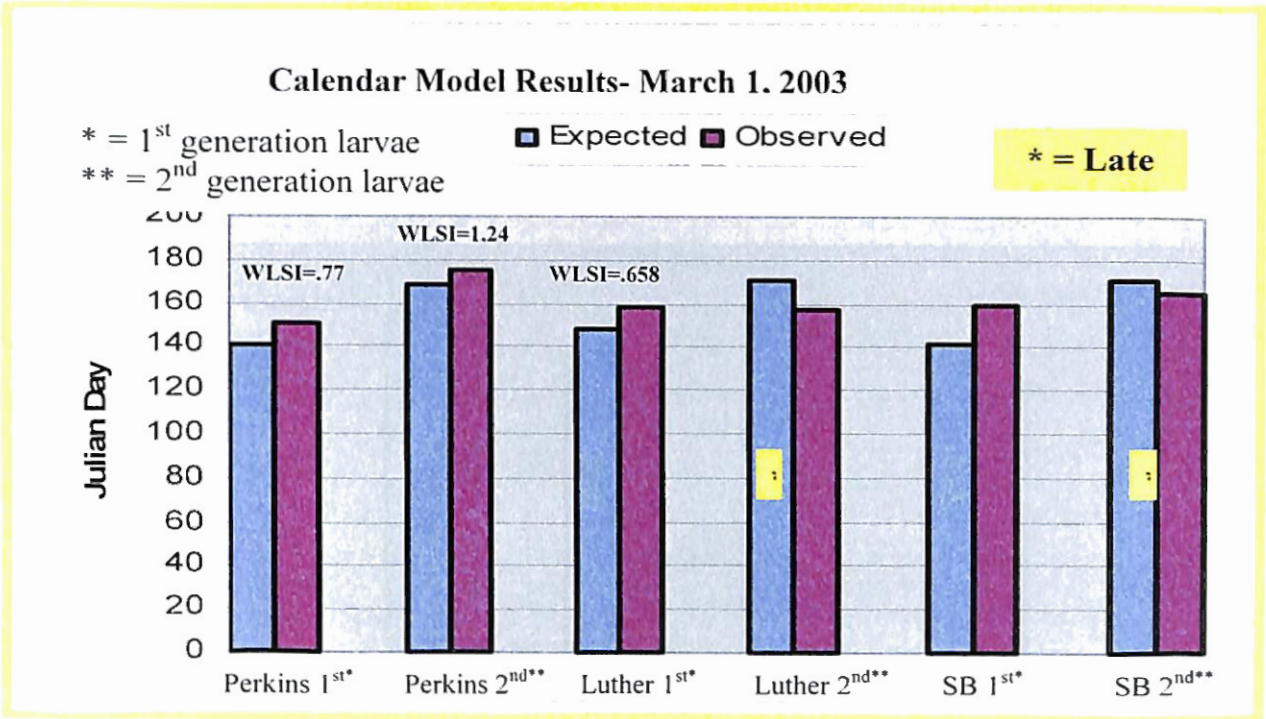


Figure 17. Weighted Least Squares Index (WLSI) values for 1st and 2nd generation larvae using the April 1 model, 2003

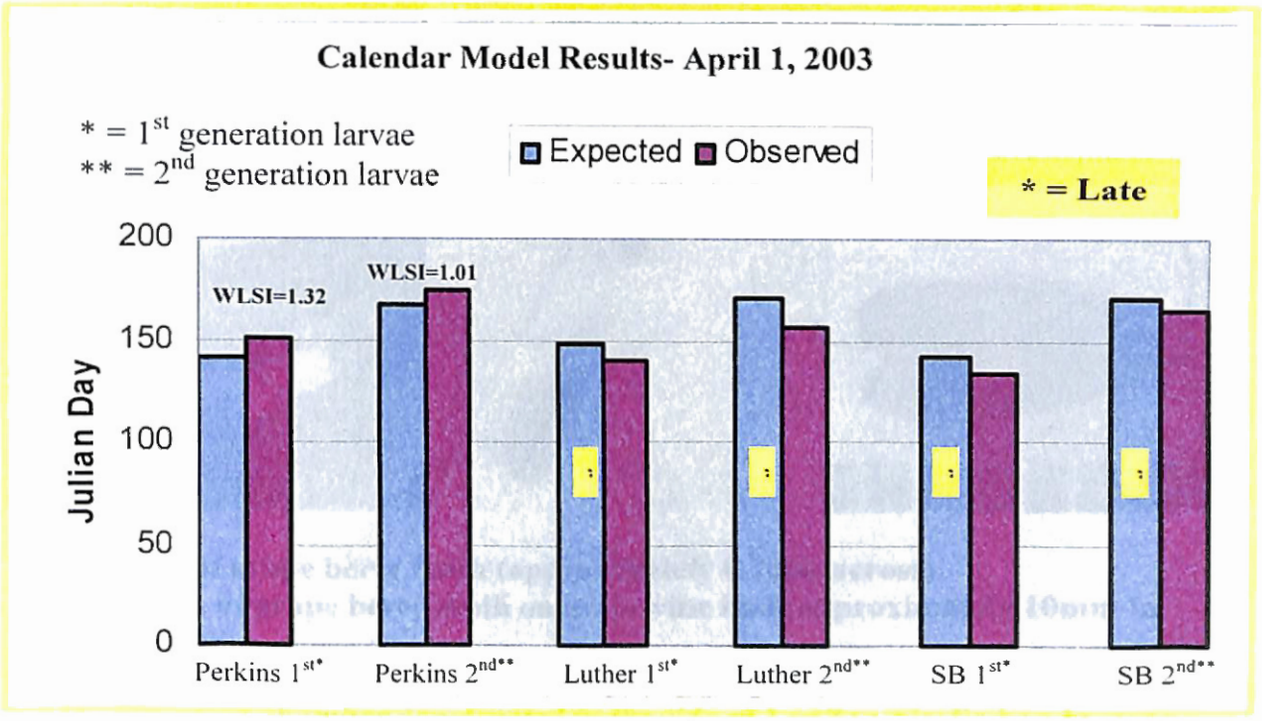
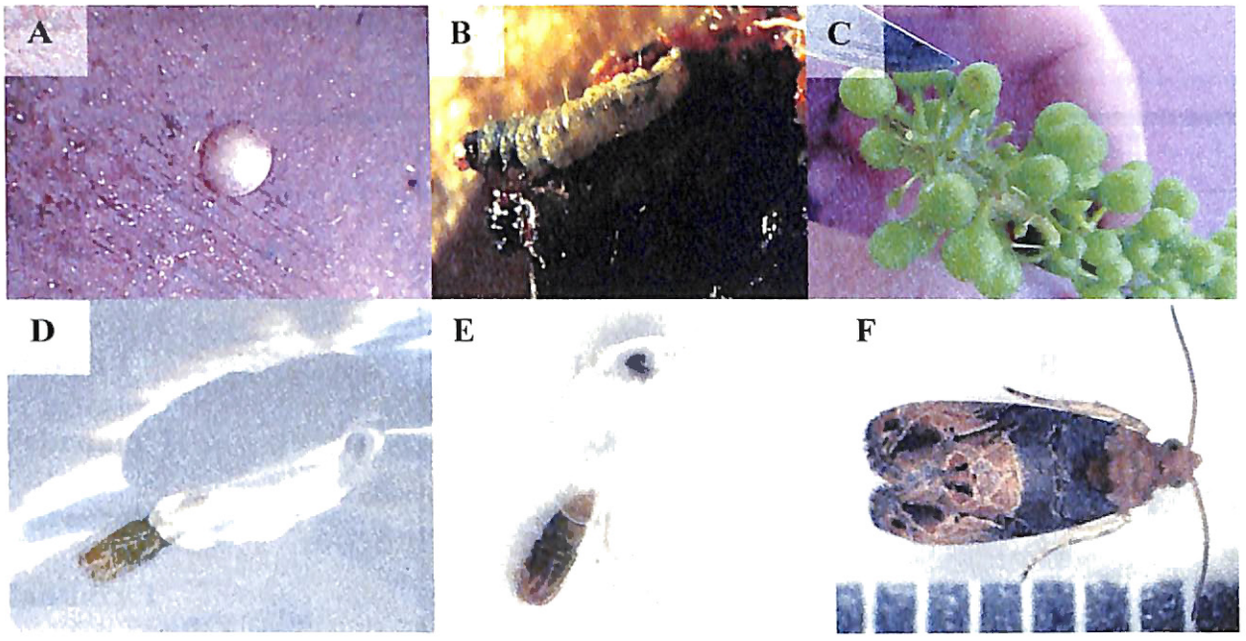


Figure 18. Incubation of Grape berry moth pupae in 1 gallon plastic bags



A. Egg of grape berry moth (approximately 0.7mm across)
B. Larva of grape berry moth on grape vine bud (approximately 10mm in length)
C. Webbing of grape berry moth on young grape fruit cluster
D. Pupation chamber constructed in the side of 1 gallon plastic bag by grape berry moth larvae, early pupae present (approximately 5 mm in length)
E. Grape berry moth near pupation into adult stage
F. Grape berry moth adult (approximately 6mm in length)

Table 2. Significant differences among the models for Event 1 (adult emergence from overwintering pupae)

Model	Mean Number of Days from Observed Event 1	t Grouping*
April	21.1667	A
Bio-fix	21.0000	A
March 1	11.1667	B
February 1	6.8333	C
Threshold	3.6667	D
January 1	3.3333	D

*Means with the same letter are not significantly different

Table 3. Significant differences among models for Event 2 (completion of oviposition)

Model	Mean Number of Days from Observed Event 2	t Grouping*
Bio-fix	16.667	A
April 1	15.000	A
March 1	11.500	B
February 1	7.167	C
Threshold	3.333	D
January 1	3.167	D

*Means with the same letter are not significantly different

Table 4. Significant differences among models for Event 3 (emergence of first generation)

Model	Mean Number of Days from Observed Event 3	t Grouping*
Bio-fix	20.667	A
April 1	19.500	A
March 1	9.833	B
February 1	8.000	B
Threshold	3.500	C
January 1	2.667	C

*Means with the same letter are not significantly different

Table 5. Significant differences among models for Event 4 (completion of oviposition by 1st generation)

Model	Mean Number of Days from Observed Event 4	t Grouping*
April 1	12.6667	A
Bio-fix	12.1667	A
March 1	9.5000	B
February 1	7.3333	C
Threshold	4.3333	D
January 1	3.1667	D

*Means with the same letter are not significantly different

Table 6. Significant differences among models for Event 5 (emergence of second generation)

Model	Mean Number of Days from Observed Event 5	t Grouping*
Bio-fix	12.833	A
April 1	11.167	A
March 1	9.667	A B
February 1	6.833	C B
Threshold	3.333	C D
January 1	2.500	D

*Means with the same letter are not significantly different

Table 7. Significant differences among models for Event 6 (completion of oviposition by second generation)

Model	Mean Number of Days from Observed Event 6	t Grouping*
April 1	11.8333	A
March 1	11.1667	A
Bio-fix	10.8333	A
February 1	6.5000	B
Threshold	5.1667	B C
January 1	3.5000	C

*Means with the same letter are not significantly different

CHAPTER IV. EVALUATION OF POTENTIAL VECTORS OF *XYLELLA FASTIDIOSA*

Abstract

A two year study was conducted to evaluate the potential threat of Pierce's Disease in Oklahoma. Three locations were chosen for evaluating this threat. To monitor for various sharpshooter species, yellow sticky traps were arranged in a diagonal manner at both high and low placements. For both years, at all three locations, no glassy-winged sharpshooters, *Homalodisca coagulta* Say, were captured. For both years, at all three locations, minimal captures (13 captured adults) for green sharpshooter, *Draeculacephala minerva* Ball, were recorded. Captures of blue-green sharpshooter, *Graphocephala atropnctata* Signoret, were minimal for 2002. In 2003, captures of blue-green sharpshooter will allow for general descriptive statistics to be performed.

The Glassy-winged sharpshooter

The glassy-winged sharpshooter, *Homalodisca coagulata* Say, is a large representative of the insect family Cicadellidae (0.5 inch) whose general color is brown to black when viewed from the side or above. The underside of the abdomen is white (Purcell and Feil 1979). The upper aspect of the head and thorax are brown or black with numerous ivory to yellowish spots. Since the early 1990's, this insect has expanded its numbers and its range. Presently, the glassy-winged sharpshooter is found in many southern California counties (Blua et al. 1999). Recently, it has been found in the lower San Joaquin Valley in Kern County, California.

This insect has rapidly gone from novelty status to a potentially serious pest. Sharpshooters feed on xylem tissue and are sap-feeders, generally accessing the water conductive tissue of their host through the stem or major leaf veins using their strong stylet-like piercing mouthparts (Purcell and Saunders 1999). As xylem feeders, sharpshooters as a group can be effective vectors of bacterial plant pathogens, particularly the xylem-limited bacterium *Xylella fastidiosa*. Once injected by sharpshooter vectors into plant xylem tissues, this bacterium multiplies and produces a gel-like material, which in combination with the multiplying pathogen blocks the water conducting xylem tissue (Purcell and Feil 1979).

This feeding initially causes die-back of leaves and shoots distal to the point of infection and, within a year or two, as the infection becomes systemic (Purcell 1997) it eventually causes the entire plant (e.g. grape vines) to collapse and die. The glassy-winged sharpshooter has a long association with Pierce's disease of grape, *Vitis riparia*

Micheaux, in the southeastern U.S. and as a vector of the causal bacterium, *Xylella fastidiosa.*

Unlike the many sharpshooter vectors associated with Pierce's disease, the glassy-winged sharpshooter is much larger and has a much broader host range. In addition, because of its greater mobility and survivability in colder climates, the glassy-winged sharpshooter can occur in greater numbers in commercial agricultural plantings (Purcell 1989). Glassy-winged sharpshooters are capable of moving into the middle of agricultural plantings and extending the threat of Pierce's disease from primarily a vineyard border problem to a vineyard-wide problem, even on large plantings.

The glassy-winged sharpshooter is not confined to riparian areas. It can easily develop large populations on dooryard ash, *Fraxinus excelsior* L., eucalyptus, *Eucalyptus parvifolia* Cambage, macadamia, *Macadamia integrifolia* Maiden, or stone fruit trees. Areas with native laurel sumac, *Rhus laurina* Nut, and commercial citrus also harbor large populations of glassy-winged sharpshooters. Large numbers of this insect migrate into crop or non-crop plantings, increasing the likelihood of bacterial transmission from even the smallest source, even though its transmission efficiency is less than some native sharpshooters (Purcell and Feil 2001).

The Green sharpshooter

The green sharpshooter, *Draeculacephala minerva* Ball, is considered to be one of two important species of insect vectors for Pierce's disease. Although it has been found on many species of herbaceous plants, it strongly prefers to feed and reproduce on grasses (Purcell 1981). It is most common on water grass, *Bulbostylis barbata* Clarke, fescues, "perennial ryegrass" and bermudagrass, *Cynodon dactylon* L. The most

common habitats for green sharpshooter are ditch banks, weedy hay fields and permanent irrigated pastures. For this reason, it is common in vineyards only when there are attractive plants in the cover crop at all times of the year (Hill and Purcell 1997). This species is rarely seen feeding on grape. The role of the green sharpshooter as a vector of Pierce's disease is based on consistent occurrence of its breeding habitats near vineyards.

The Blue-green sharpshooter

The blue-green sharpshooter, *Graphocephala atropunctata* Signoret, is considered to be one of the most important vectors of Pierce's disease in coastal California. Woody plants, including grapevines, are favored for feeding and reproduction. The list of plants on which it regularly feeds is quite large, but it favors certain plant species over others, especially for laying eggs. The most common riparian plants on which it is found in California include grape, blackberry, *Rubus spp.*, elderberry, *Sambucus canadensis* L, mugwort, *Artemisia vulgaris* L, stinging nettle, *Urtica dioica* L, and snowberry, *Symphoricarpos occidentalis* Hook. Ornamental landscapes located in residential areas or parks, present an environment where this species would favor roses, *Rosa* spp., fuschia, *Phygelius* spp., ivy, *Chlorphytum* spp., and a variety of ornamental shrubs or trees. Unlike other important vectors of Pierce's disease in California, the blue-green sharpshooter commonly occurs on commercial grapevines near riparian vegetation. Similar to other xylem-feeding insects, it prefers new growth on plants that are in a succulent condition. This is probably the major reason it prefers riparian areas in California (Hill and Purcell 1995a).

Adult blue-green sharpshooters are long-lived. There is usually only a single generation per year. A few adults may lay eggs a few weeks after they mature, resulting

in a partial second generation, but most females require a period of cool temperatures to mature reproductively and do not lay eggs until the following spring. A high percentage of adults survive the winter, but not much is known of their behavior during winter.

Like other vectors; adult blue-green sharpshooters retain infectivity with *Xylella fastidiosa* for an indefinite period. Therefore, adults that acquire the bacterium during the autumn can introduce *Xylella fastidiosa* into plants during the following spring. The spatial pattern of Pierce's disease in north coast California vineyards reflects the spring dispersal pattern of blue-green sharpshooter adults. To reduce the spread of Pierce's disease near riparian sources of blue-green sharpshooter, growers should reduce the number of adult sharpshooters entering vineyards in spring months (Purcell 1975).

The objective of this study was to define the potential threat from vectors of Pierce's disease in Oklahoma. After potential vectors are defined, an appropriate sample unit will be determined and dispersion patterns were developed.

Material and Methods

A two year evaluation of the potential threat of vectors of Pierce's disease in Oklahoma was conducted. The following locations in Oklahoma were used in evaluating this threat: Perkins Research Station, Perkins; Tres Suenos Vineyard, Luther; and Stone Bluff Vineyard, Stone Bluff. Figure 1 provides a map of the monitoring locations across the state.

To define the vector status in Oklahoma, yellow sticky traps (Trece Incorporated, Salina, Calif.) were used to monitor for various sharpshooter species, especially those suspected of transmitting Pierce's disease. To effectively determine the common species of leafhoppers and their distribution in Oklahoma grapes, yellow sticky traps were placed

in a diagonal pattern across the vineyards, at both high and low placements. Traps were placed in vineyards starting April 1 and remained in the field through August. Yellow sticky traps were collected twice weekly and brought back to the lab for inspection using a stereomicroscope. In addition, Tangle-Trap© insect trap coating was applied to the top surface of each of five leaves. Sticky leaves were collected once weekly and brought back to the lab for inspection using a steromicroscope.

Results/Discussion

For both years (2002 and 2003), at all three locations, no glassy-winged sharpshooters were captured on yellow sticky traps or coated grape leaves. For both years (2002 and 2003), at all three locations, minimal captures (13 captured adults) for green sharpshooter were recorded. Due to the lack of data recovered for these organisms, no analysis was performed.

In 2002, minimal captures of blue-green sharpshooter were recorded. Due to the lack of data no analysis was performed. In 2003, at all three locations, captures of blue-green sharpshooters (Figures 2-4) provided sufficient information to eventually determine general descriptive statistics for field samples. Two-hundred and six blue-green sharpshooters were captured in Payne County. First capture of blue-green sharpshooter occurred May 1 and peaked May 30. Blue-green sharpshooter activity resumed through mid-July and terminated July 24. Two-hundred and thirty-five blue-green sharpshooters were captured in Oklahoma County, first capture occurred May 1 with peak activity arriving the first of June and adjourning July 30. One-hundred and eighty-six blue-green sharpshooters were captured in Wagoner County. First capture of blue-green

sharpshooter occured May 3 and peak activity arrived May 28. Activity of blue-green sharpshooter terminated July 17.

Results of this study indicate that a minimal threat exists from Pierce's disease and the vector complex in Oklahoma. However, the fact that grape production is relatively new to the state leads one to believe there is still the possibility of the arrival of a vector complex capable of transmitting Pierce's disease. This study also revealed the presence of blue-green sharpshooter in Oklahoma. If Pierce's disease is ever found in Oklahoma, a potential vector with a wide host range does exist.

There is the possibility that movement of the blue-green sharpshooter could be exploited in IPM programs. By applying barrier sprays around the perimeter of vineyards early in the season, growers may suppress subsequent colonization. This approach may be particularly effective in vineyards under clean cultivation, which have little alternate vegetation available for overwintering of sharpshooters. At sites where vegetative cover within the vineyard provides overwintering capabilities for adults, perimeter sprays may be less effective in preventing colonization.

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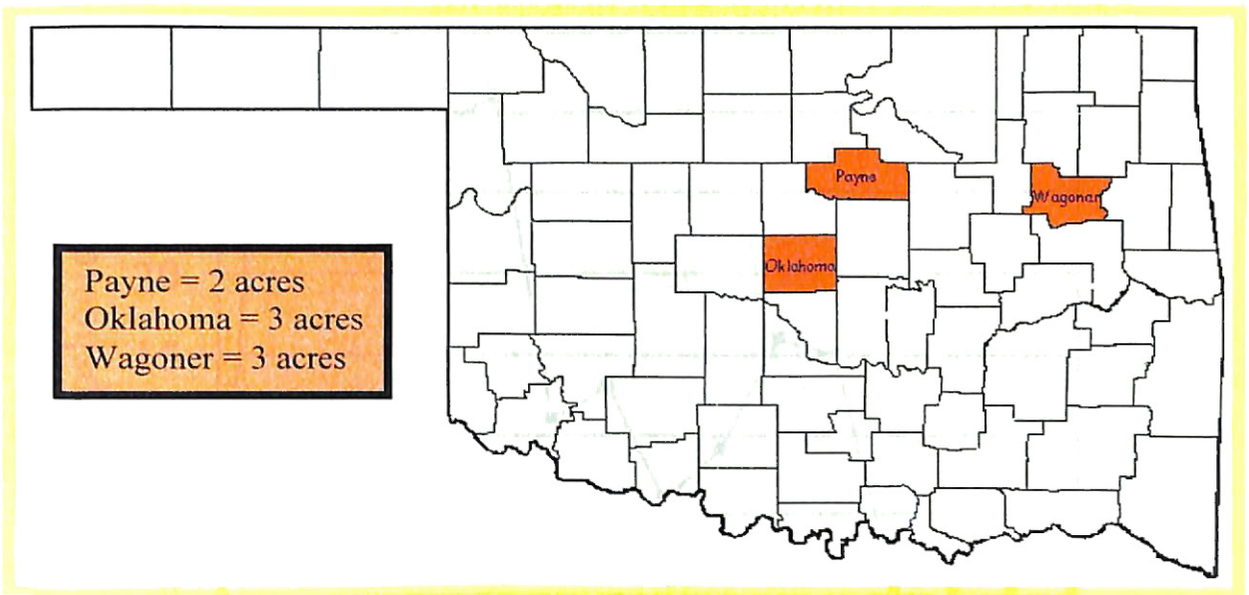
Fig. 1. Oklahoma map showing the location of the various trapping sites used for monitoring potential sharpshooter vectors.



Payne County – Perkins Research Station
Oklahoma County – Tres Suenos Vineyard
Wagoner County – Stone Bluff Vineyard

Figure 2. Yellow sticky trap captures of blue-green sharpshooter for Perkins, Ok, 2003

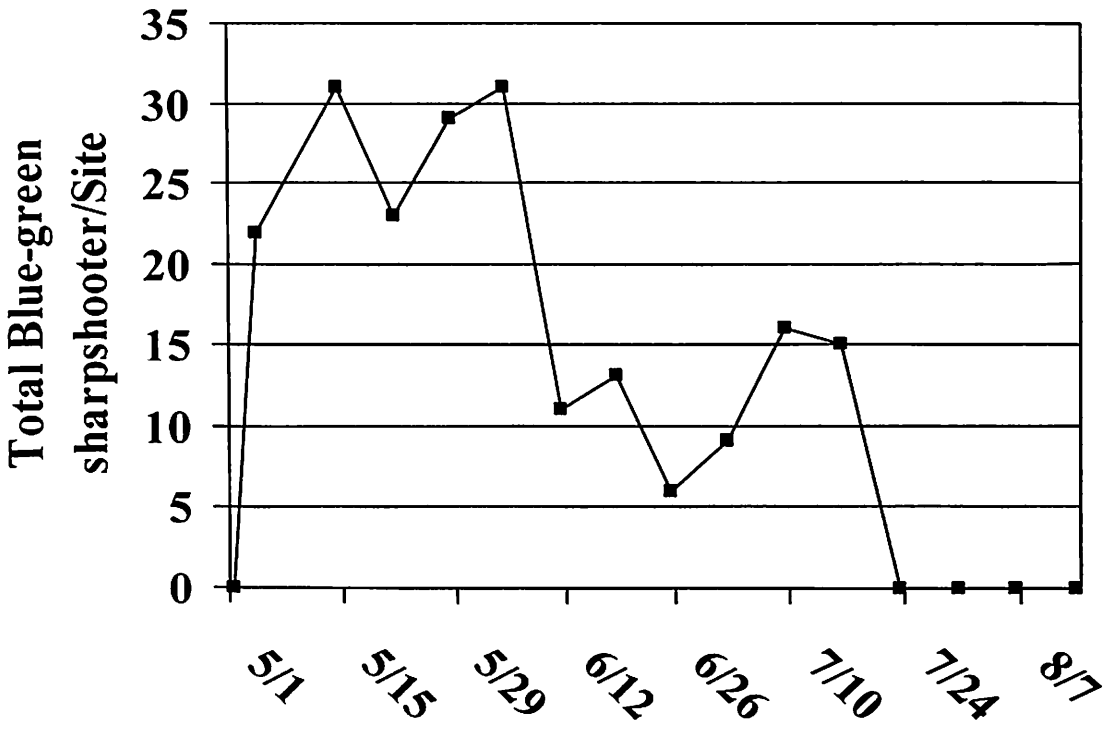


Figure 3. Yellow sticky trap captures of blue-green sharpshooter for Luther, Ok, 2003

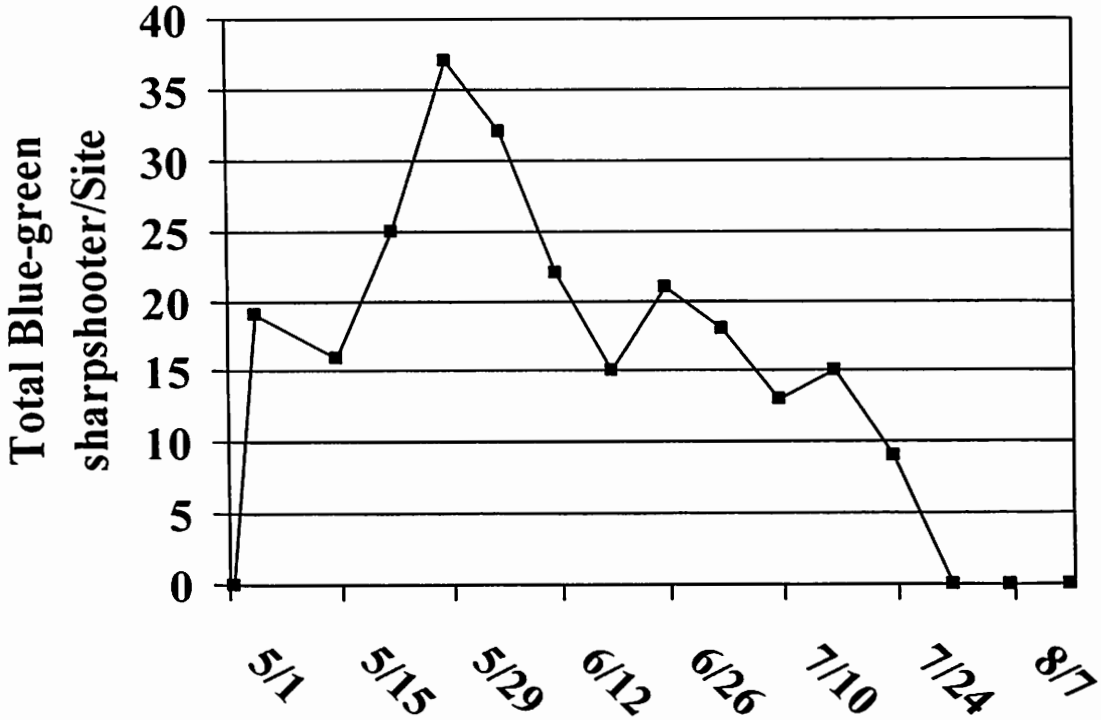
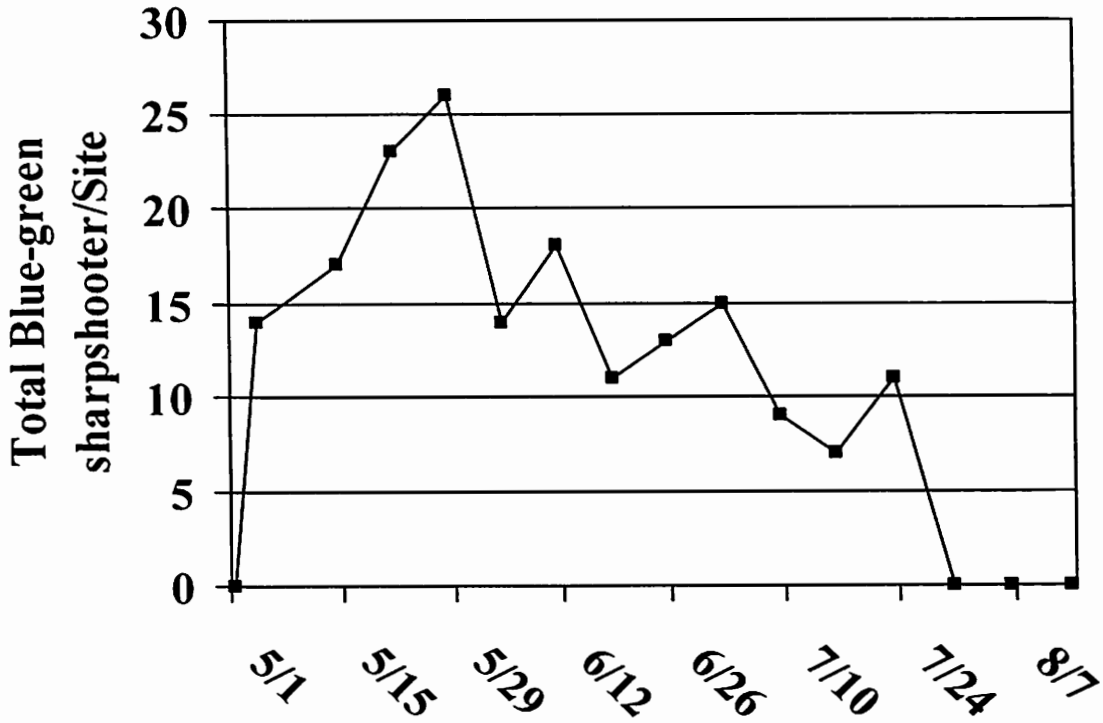


Figure 4. Yellow sticky trap captures of blue-green sharpshooter for Stone Bluff, Ok, 2003



CHAPTER V: SUMMARY AND CONCLUSIONS

The pest complex of grapes in Oklahoma appears capable of significant variation from year to year. The current major pest is the grape berry moth. In 2002 and 2003 more grape berry moths were captured than any other pest species in Oklahoma. In addition, all life stages were noted for grape berry moth during this 2 year study. Comparing predictions generated by developmental models for grape berry moth to observed events helped determine the accuracy of predictive models for these life stages. Models initiated on January 1 of each year, or those begun based on developmental temperature threshold (10°C) yielded the most precise predictions of phenological events of the grape berry moth. These two predictive models were significantly more accurate when comparing predicted and observed phenological events to the previous standard of using first capture (bio-fix) of adult males to initiate accumulation of degree days. In addition, models initiated on January 1 or at developmental threshold also preceded phenological events and predicted their arrival nearly two weeks prior to the other models. These latter two findings are more desirable for development of IPM programs because they anticipate arrival of damaging stages of grape berry moth and coincide better with observed phenological events.

Trap captures for Grape root borer, *Vitacea polistiformes* (Harris), were minimal in 2002 and 2003, (Figures 1-6). In 2002, trap captures of male moths occurred throughout the growing season, no pupal skins were found during routine scouting procedures. In Payne County, 23 male grape root borer moths were captured. In Oklahoma County, 18 male grape root borer moths were captured and in Wagoner County, 39 were captured. Again in 2003, trap captures of male moths occurred throughout the growing season and no pupal skins were found during routine scouting

procedures. In Payne County, 26 male grape root borer moths were captured. In Oklahoma County, 25 male grape root borer moths were captured and in Wagoner County, 36 were captured. No immediate threat of grape root borer should be expected, nor was any observed. However, grape root borer can take as long as three years to complete its life cycle, with the majority of this life cycle spent as a larva under the soil surface feeding on the root system. As a precaution, cultural practices for controlling larvae should be reviewed occasionally by Oklahoma grape producers. As vineyard size expands and plants continue to age in Oklahoma the grape root borer may become a more severe pest over time.

For both years, at all three locations, no glassy-winged sharpshooters, *Homalodisca coagulta* Say, were captured. For both years, at all three locations, minimal captures (13 captured adults) for green sharpshooter, *Draeculacephala minerva* Ball, were recorded. In 2003, at all three locations, captures of blue-green sharpshooter, *Graphocephala atropunctata* Signoret appeared to be on the rise, resulting in an opportunity to work on developing dispersion patterns for this insect. The threat of Pierce's disease and a vector complex appears to be minimal.

Green stinkbug, *Acrosternum hilare* Say, and brown stinkbug, *Euschistus servus* Say, were found to be pests of grapes. In 2002 and 2003, mating began approximately the 15th of June. Both green and brown stinkbugs were captured in yellow sticky traps. At the conclusion of mating; eggs were found on stems, leaves, and berries of grape plants. Stinkbug infestations were documented during general scouting practices in Wagoner County. Mating activity was confirmed and a total of 39 adult stinkbugs were captured via yellow sticky traps. Vegetative and fruiting structures were scouted for

infestation following positive identification of adult stinkbug. Peak populations of stinkbug nymphs occurred June 11 to June 28 with up to 24% fruiting clusters infested (Figure 7).

Digital pictures (Figure 8) of green and brown stinkbug nymphs were taken to document direct feeding on berries. We suspect that stinkbugs migrate from existing soybean, *Glycine max* (L.), (or other leguminous plants) which surround many vineyards, particularly in northeast Oklahoma. Many northeast counties in Oklahoma are involved in soybean production, vineyards located in this part of the state may be more susceptible to stinkbug attack.

Although production of grapes in Oklahoma is relatively new, the pest complex is likely to grow. The use of IPM tools that currently exist, and development of new IPM tools, should be encouraged. The initiation and development of such tools will lead to a more economic method of pest management that is less stressful to the environment and to the grower that pays to control these pest problems.

Figure 1. Grape root borer pheromone trap captures for Payne County, 2002

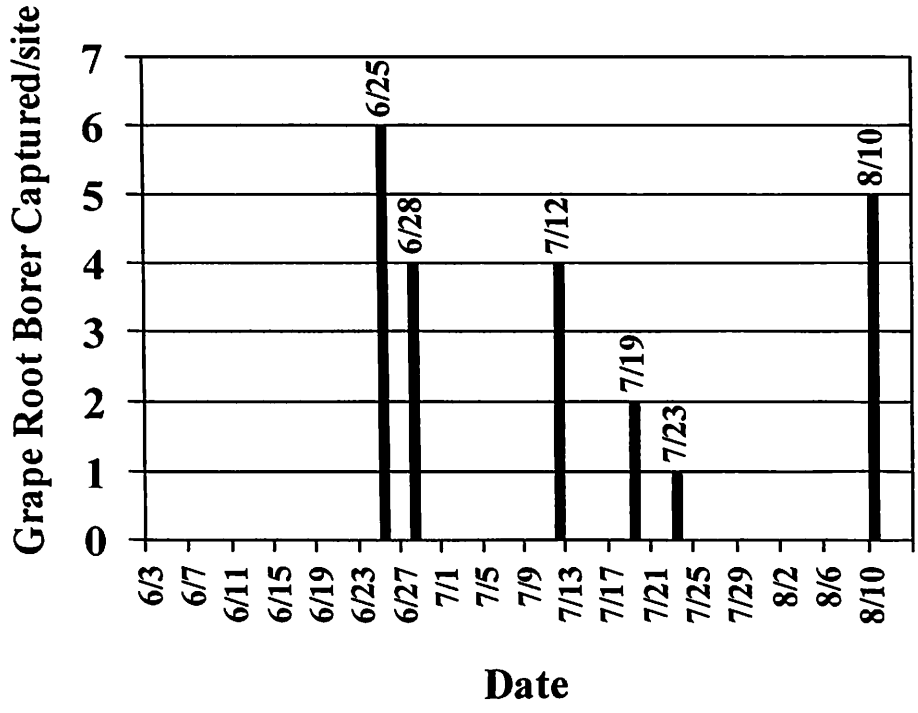


Figure 2. Grape root borer pheromone trap captures for Oklahoma County, 2002

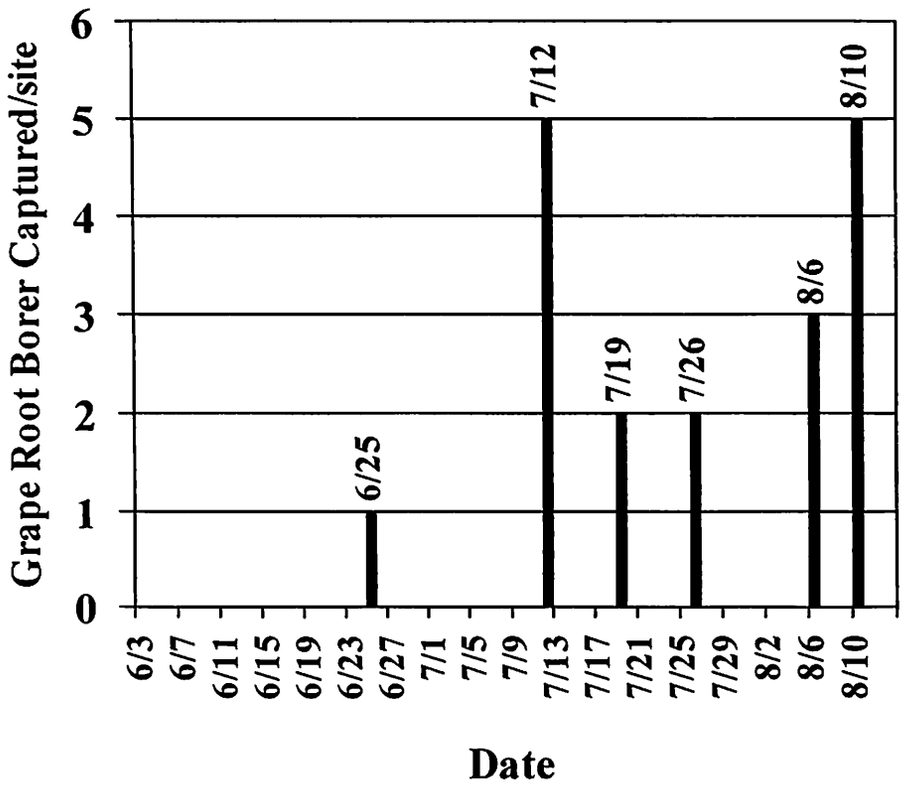


Figure 3. Grape root borer pheromone trap captures *for Wagoner County, 2002*

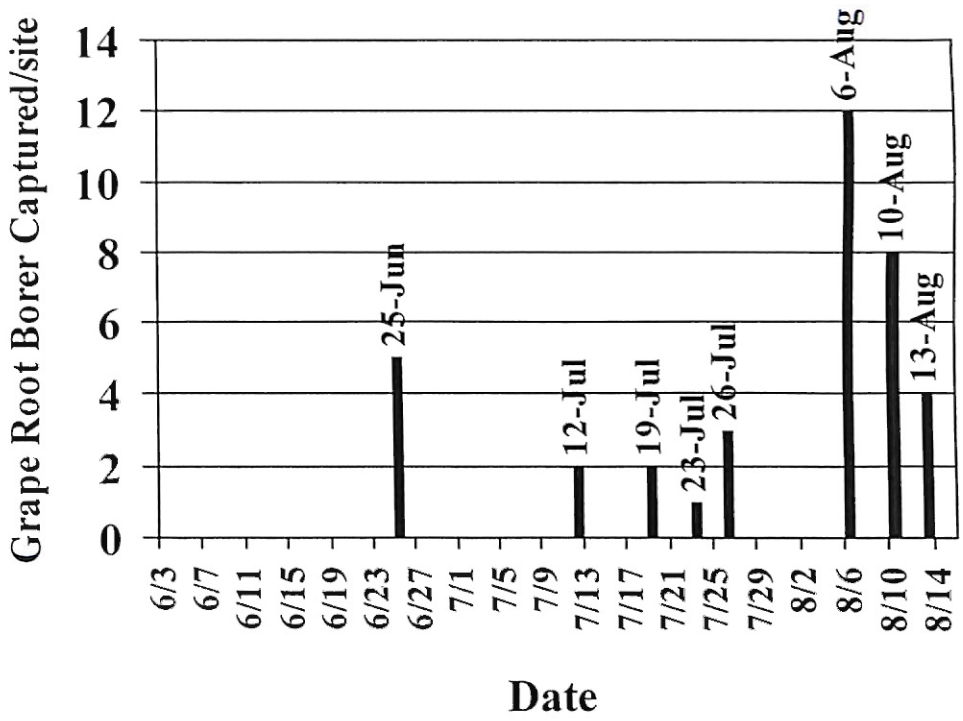


Figure 4. Grape root borer pheromone trap captures for Payne County, 2003

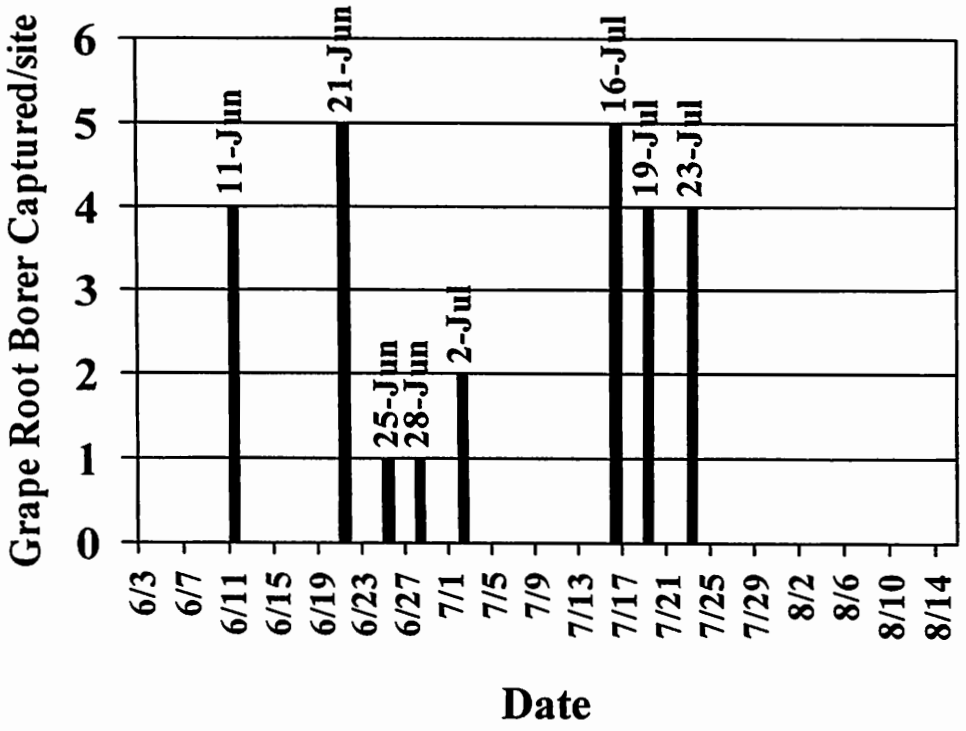


Figure 5. Grape root borer pheromone trap captures for Oklahoma County, 2003

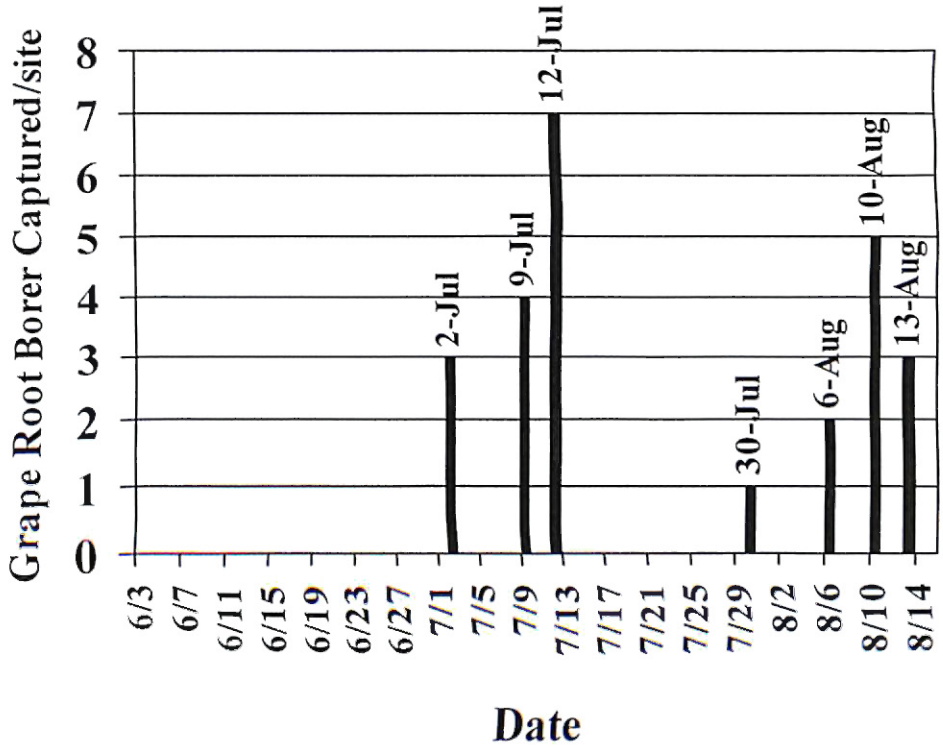


Figure 6. Grape root borer pheromone trap captures for Wagoner County, 2003

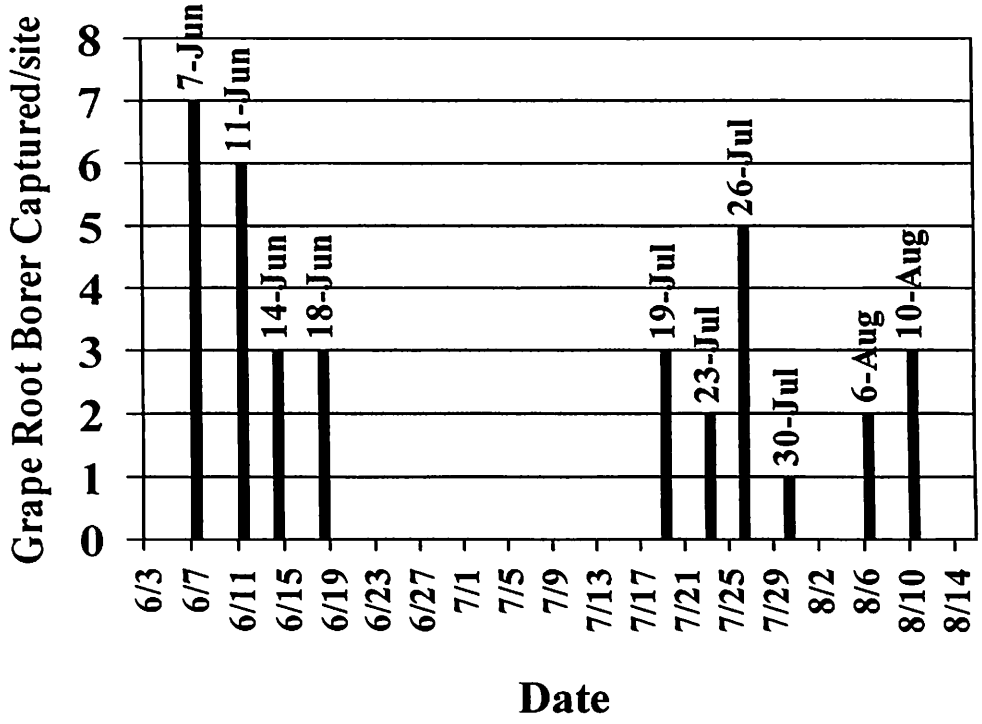


Figure 7. Stinkbug infestations for Wagoner County, 2002

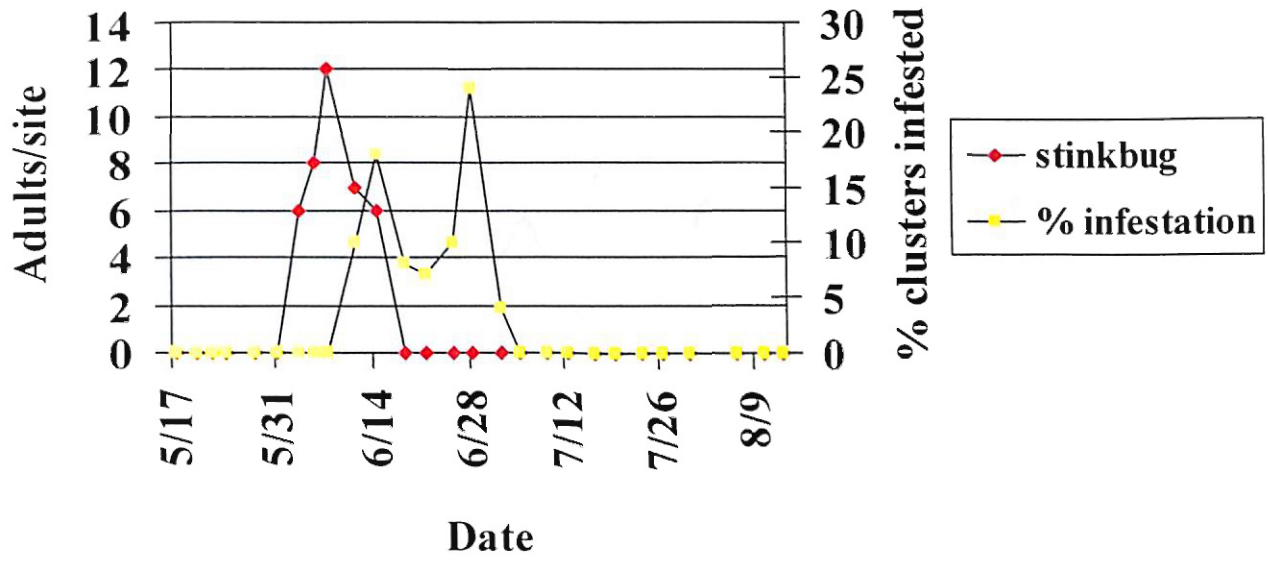
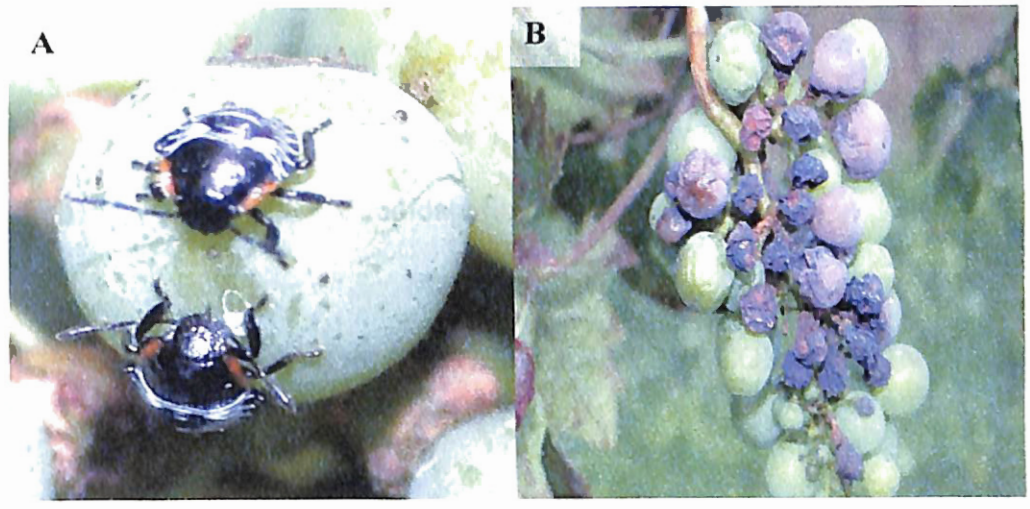


Figure 8. Stinkbug feeding on grape individual berry (A) and resulting damage to grape cluster (B)



Note – Stinkbug damage on grapes occurred in 2002 and 2003 at Stone Bluff Cellars, Stone Bluff, OK. Vineyards located in the northeast part of the state may be more susceptible to stinkbug attack.

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