ECOLOGY, BEHAVIOR, IMPACT, AND AN INTEGRATED PEST MANAGEMENT STRATEGY FOR THE ORANGESTRIPED OAKWORM, *ANISOTA SENATORIA* (J. E. SMITH), IN THE URBAN LANDSCAPE

by

Mark Alan Coffelt

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APPROVED:

P. B. Schultz, Chairman

L. T. Kok

R. L. Pienkowski

R. D. Fell

R. J. Stipes

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Committee Chairman: Peter B. Schultz
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(ABSTRACT)

The biology of *Anisota senatoria* J. E. Smith (Lepidoptera: Saturniidae) was examined through ecological studies of within-tree distribution and dispersion, and the influence of a tree growth regulator on development and survival. Biological characteristics examined egg mass size and development, pheromone attraction, response to blacklight traps, adult emergence, laboratory development, pupal mortality and comparison of first versus second generation development time, fecundity and amount of infestation. Within-tree distribution of life stages showed significant differences between low (1.7-3.6 m in height), middle (3.7-5.5 m) and high (5.6-7.6 m) strata. Dispersion indices generated from Taylor's power law showed aggregation was greatest among early instars, followed by third instars and late instars. A fixed level precision sampling plan was developed based on the number of eggs and early instars present in low strata. The tree growth regulator paclobutrazol significantly reduced *Q. phellos* L., willow oak, growth, especially one and two years posttreatment. One year posttreatment, paclobutrazol treatments significantly slowed development and decreased survival of early instars, but the opposite relationship was

found with late instars.

Behavior studies showed that increased *A. senatoria* survival occurred with increased group size. Laboratory and field experiments revealed critical group sizes for survival of 1-3 larvae and between 25-50 larvae.

Anisota senatoria defoliation impact and frass were measured. Growth and root starch were significantly reduced with increased defoliation in *Quercus palustris* Muench., pin oak, but *Q. phellos* root starch was not reduced. Reduction in starch content in *Q. palustris* may have been related to additional stress factors. Landscape fabrics were a reliable sampling method for frass. Frass was used as a method for differentiating larval instars and predicted defoliation of *Q. palustris*.

An integrated pest management (IPM) program was developed that included information on native parasites, host plant preference, a citizen survey, and aesthetic indicators. Four egg parasite species including an *Aprostocetus* new species, five larval parasites and eight hyperparasites were collected. Host plant preference experiments indicated that *Q. alba* L., white oak, was least preferred by *A. senatoria*. A citizen survey provided a framework for designing an IPM program. Monitoring and establishing an aesthetic injury level of 25% defoliation decreased pesticide volume without an attendant increase in damage. The number of egg masses (threshold) that caused 25% defoliation ranged from one to nine.

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Introduction and

Literature Review

Anisota senatoria (J. E. Smith) (Lepidoptera: Saturniidae, orangestriped oakworm) is native to North America and was originally described by Dr. James Edward Smith (Smith 1797) of England from colored illustrations made by John Abbot. Ferguson (1971) assumed the type locality to be Screven or Bulloch counties in Georgia, approximately 80 km east of the Atlantic Ocean. Riotte & Peigler (1981) assumed the type locality also included six southeastern Georgia counties that bordered the Atlantic Ocean.

Anisota senatoria belongs to the subfamily Citheroniinae (Covell 1984); however, this subfamily has been frequently elevated to family rank (Riotte & Peigler 1981). It is a primitive subfamily of Saturniidae and is exclusively New World in distribution. *Anisota* is primarily a Nearctic genus, and probably originated in Mexico or Central America as specialized feeders on *Quercus* (oak) species. There are 15 *Anisota* species, and Riotte & Peigler (1981) classified these species into 4 groups according to larval and adult habits and geographical distributions. These groups include the *A. stigma* group (four species), *A. senatoria* group (three species), *A. pellucida* group (four species), and the Mexican group (four species). They provided a key to adults and

mature larvae and described phylogenetic relationships.

Distribution. *Anisota senatoria* has a wide distribution in North America. Riotte & Peigler (1981) examined *A. senatoria* specimens from 19 states, including Virginia; the northern range limit is southwestern Ontario, Canada and Maine. In the northeastern United States, *A. senatoria* can be abundant (Hitchcock 1958). This insect is considered rare in the southeast (Ferguson 1971) and southern Florida where sporadic populations can occur (Riotte & Peigler 1981). The western extent of its range is eastern Texas (Riotte & Peigler 1981). In the mid-western states, it is reported from Minnesota, Wisconsin, Michigan, Ohio, and Indiana (Davis 1934, Houser 1918, Johnson & Lyon 1988, Baker 1972).

Biology. *Anisota senatoria* biology was reported by Lintner (1889), Lugger (1890), Felt (1905), Baker (1972), and Riotte & Peigler (1981). Adults eclose from overwintering pupae in late June and are present throughout July (Hitchcock 1958). Mated pairs are found on grass blades, low bushes, or tree trunks (Lintner 1889, Hitchcock 1958). Peigler & Williams (1984) reported that male *A. senatoria* pursue females from approximately 1130 to 1530 h EST. Eggs are yellow (Hitchcock 1961b, Riotte & Peigler 1981) and oviposition occurs on leaf undersides in masses of 200-700 (Hitchcock 1958). Egg masses are deposited on the terminal twigs of lower branches 3-4 m above the ground (Lintner 1889, Hitchcock

1958). Oviposition occurs throughout July (Becker 1938). Eggs eclose in 7-10 days (Becker 1938), and gregarious green-yellow larvae skeletonize leaves (Hitchcock 1958, Baker 1972). There are five instars of *A. senatoria* (Lintner 1889, Riotte & Peigler 1981). Larvae have a pair of black recurved horns on the mesothoracic segment. Fifth instars are approximately 5 cm long, and are black with eight yellow-orange stripes and numerous sharp spines (Solomon et al. 1980). Fifth instars are less gregarious and consume entire leaves except for the main vein (Baker 1972). Defoliation occurs in late August through September (Hitchcock 1958). During September or October, larvae crawl considerable distances seeking suitable habitats to pupate (Hitchcock 1958). Larvae burrow 7-10 cm in the soil and pupate (Felt 1905). The 2-3 cm brown pupae are covered with short spines and have sharp bifid cremasters (Hitchcock 1958, Riotte & Peigler 1981). Pupae used their spines and cremasters to maneuver and protrude through the soil in late June (Lintner 1889, Lugger 1890). Ehrlich et al. (1969) described characteristics for *A. senatoria* pupal sex determination. There are one and possibly two generations a year, depending on location (Hitchcock 1958, Baker 1972).

Lawson et al. (1982, 1984) reported on the nutritional ecology of *A. senatoria*. When it was reared on six *Quercus* species, differences in growth rates were nonsignificant between species. Relative consumption rate and conversion of

ingested food was significantly correlated with leaf nitrogen concentration; larval utilization was not influenced by leaf tannin concentration (Lawson et al. 1982). Lawson et al. (1984) compared several nutritional indices of a spring feeding caterpillar, *Alsophila pometaria* (Harr.) (Lepidoptera: Geometridae), the fall cankerworm, and the late season *A. senatoria* defoliator. They suggested that *A. senatoria* favored feeding efficiency over growth rate.

Host plants. *Quercus* species are preferred hosts, and some *Quercus* species appear to be favored over others (Hitchcock 1961a, 1961b). Solomon et al. (1980) reported that forest stands of *Q. rubra* L., red oak, and *Q. alba* L., white oak, on upland sites were the most heavily defoliated. Herrick (1935) reported a preference for *Q. alba* and *Q. ilicifolia* Wang., scrub oak. However, Hitchcock (1961b) reported that *A. senatoria* preferred to oviposit on trees of *Q. velutina* Lam., black oak, rather than *Q. alba*, although they developed on both *Quercus* species. *Anisota senatoria* fed on *Q. alba* and *Q. rubra* in Massachusetts, *Q. velutina*, *Q. ilicifolia*, and *Q. coccinea* Muenchh., scarlet oak, in Pennsylvania, and on *Q. ilicifolia* and *Q. prinus* L., chestnut oak in New York (Lintner 1889). Hutchings (1926) reported *Q. alba* was attacked by *A. senatoria* in western Ontario, Canada. In southeastern Virginia, *A. senatoria* frequently defoliated *Q. palustris* and *Q. phellos* (Coffelt & Schultz 1991a).

Quercus species with tough, pubescent, or evergreen leaves were less preferred by *Anisota* species (Riotte & Peigler 1981).

Anisota senatoria infestations were not restricted to *Quercus* species. Dimmock (1885) reported *A. senatoria* fed on *Betula alba* L., white birch, and Headlee (1918) reported *Betula* species were attacked in New Jersey. *Anisota senatoria* attacked *Acer* species, maple, *Corylus* species, hazelnut, and *Carya* species, hickory (Becker 1938, Houser 1918). Riotte & Peigler (1981) found *Castanea* species, chestnut and chinquapin, damaged by *Anisota* species. Stimmel (1988) reported *A. senatoria* fed on *Castanea* species, *Fagus* species, beech, and *Hamamelis* species, witch-hazel, when *Quercus* foliage was depleted. Field populations of *A. senatoria* fed on *Aesculus hippocastanum* L., horse chestnut, in Norfolk, VA (Coffelt, unpublished data). Reports that *A. senatoria* fed on *Rubus* species, raspberry, (Dimmock 1885, Covell 1984) were probably incorrect. These reports were based on the observation by C. V. Riley that *A. senatoria* oviposited on *Rubus* species leaves, but Lintner (1889) stated that the larvae did not feed.

Pest status. *Anisota senatoria* was characterized as an occasional pest of forest trees and urban plantings (Felt 1905, Houser 1918, Becker 1938). Johnson & Lyon (1988) reported forest trees were usually attacked more frequently,

but trees along parks and city streets were occasionally attacked. Beal (1952) reported southeastern forest hardwoods withstood considerable defoliation and *A. senatoria* was more important as a shade tree and ornamental defoliator than as a forest stand defoliator. *Anisota senatoria* was listed as one of 30 major shade tree pests in the United States (Olkowski et al. 1978) and a major oak defoliator in the southern states (Solomon et al. 1980). Many early reports of *A. senatoria* defoliation were published but damage was not quantified. Claypole (1883) wrote that millions of *A. senatoria* larvae destroyed oak foliage in Pennsylvania forests. Lintner (1889) reported many *A. senatoria* were found annually in New York, and during one summer large populations of crushed larvae caused slippage of railroad wheels. Felt (1905) reported *A. senatoria* was common in New York and annually caused considerable injury to oaks. Oaks near Kalamazoo, Michigan were completely defoliated from 1866-1869 (Felt 1905). *Anisota senatoria* was the most significant defoliator in Minnesota (Lugger 1890). Forest, shade tree, and nursery oaks in Maryland were defoliated by *A. senatoria* (Symons & Gory 1913). In New Jersey, serious *A. senatoria* damage was reported on oaks in 1915 and 1917 (Headlee 1917, Headlee 1919). Widespread outbreaks occurred from 1918-1920 in Ohio (Houser 1918). Davis (1934) reported *A. senatoria* defoliated oaks in Indiana and attained pest status. In Ontario, Canada,

the first report of damaging *A. senatoria* populations appeared in 1923 (Ross & Caesar 1924).

Major outbreaks occurred in Connecticut, Michigan, New Jersey, New York, and Pennsylvania (Johnson & Lyon 1988). During 1958-1960, Hitchcock (1961a) reported *Lymantria dispar* (L.) (Lepidoptera: Lymantriidae), gypsy moth, and *A. senatoria* were the first and second most damaging pests of oaks in Connecticut. An unprecedented outbreak occurred in 1958 where more than 15,000 ha of trees were defoliated, but by 1960 defoliation was reduced to 10.5 ha in Connecticut (Hitchcock 1958, 1961a). In 1987, 4,453 ha were defoliated in Rhode Island, but by 1989 only 40.5 ha were defoliated (Hofacker et al. 1990). *Anisota* species (*A. virginiensis*, *A. senatoria*, and *A. stigma*) and *Cameria* species (Lepidoptera: Gracillariidae), oak leaf miners, defoliated or browned 36,500 ha in Mississippi (Solomon & Cook 1978). Riotte & Peigler (1981) reported that *A. senatoria* were very common and attained pest status in eastern Texas, northern Louisiana, and Missouri. Damaging field populations of *A. senatoria* were found in Missouri forests (Ignoffo et al. 1973). Damaging populations of *A. senatoria* warranted pesticide treatment in Maryland (Smith & Raupp 1986). *Anisota senatoria* caused extensive defoliation of landscape *Quercus* species in southeastern Virginia and an IPM approach was initiated (Coffelt & Schultz 1987, 1989, 1990a, 1991a).

Control methods. Arsenical compounds, rotenone pesticides, mevinphos, and dichloro diphenyl trichloroethane (DDT) were applied to control *A. senatoria* infestations before 1965. Lintner (1889) and Lugger (1890) reported that valuable ornamental and shade trees could be sprayed with London purple (calcium arsenite and arsenate) or Paris green (copper arsenate) to control *A. senatoria*. Becker (1938) recommended lead arsenate to control large *A. senatoria* infestations. Safened calcium arsenate and lead arsenate effectively controlled *A. senatoria* larvae (Potts 1944). The botanical insecticide rotenone, derived from *Derris* species roots and ground into a powder, effectively controlled *A. senatoria* (McIndoo et al. 1919). Fourth and fifth instar *A. senatoria* experienced 54-100% mortality when fed oak leaves sprayed with *Derris* species powder and arsenical mixtures (Potts & Whitten 1940). Donley (1959) applied the organophosphate compound mevinphos to trunks of sapling oaks that each had 25 *A. senatoria* larvae and found 0% mortality after 24 hours and 100% mortality after 72 hours.

Pesticides that were applied to early instar *A. senatoria* caused higher mortality compared with late instars. Friend (1946) applied DDT by helicopter to oaks in late August to control *A. senatoria* third-fifth instars. Mortality was poor and severe defoliation occurred, higher mortality could be achieved with first and second instars. Kerr (1951) applied

lead arsenate and DDT in early September to oaks that contained early instar *A. senatoria* and 98% mortality occurred. Hitchcock (1958) reported that DDT and lead arsenate applied to early instars caused higher mortality compared with late instars.

Pesticides that could be incorporated into an IPM program have been evaluated for *A. senatoria* control from 1973 to the present. Ignoffo et al. (1973) and Kaya (1974) showed *Bacillus thuringiensis* var. *alesti* was effective in controlling all five instars of *A. senatoria*. Pyrethroid insecticides such as bifenthrin, fenpropathrin, and cyfluthrin caused 100% mortality of first-third instar *A. senatoria* (Schultz & Coffelt 1986a, Coffelt & Schultz 1991b). Avermectin B_1, a macrocyclic lactone derived from *Streptomyces avermitilis*, caused 96% mortality of *A. senatoria* larvae, but neem seed extract, derived from *Azadirachta indica* (A. Juss.) trees, was not effective against *A. senatoria* larvae and caused only 20% mortality (Schultz & Coffelt 1986a). Organophosphate and carbamate compounds were traditionally used to control *A. senatoria*. Acephate caused 90% mortality and carbaryl 100% mortality of early instar *A. senatoria* (Schultz & Coffelt 1986b, 1989).

Mechanical controls were first proposed by Lintner (1889) and Lugger (1890). Lintner (1889) suggested that *A. senatoria*

moths could be destroyed as they appeared among grass blades, lower branches could be pruned to decrease oviposition by gravid females, and trenches could be constructed around infested tree trunks to trap migrating larvae. Lugger (1890) emphasized mechanical control by pruning infested branches and burning *A. senatoria* larvae. More recently, strategies that utilize IPM have been established based on plant injury levels (Coffelt & Schultz 1990b, 1991c).

Natural control. Numerous hymenopteran and dipteran parasites of *A. senatoria* have been reported (Schaffner & Griswold 1934, Muesebeck et al. 1951, Herting & Simmonds 1976, Riotte & Peigler 1981, Peigler 1985). Hitchcock (1958) reported 17 parasite species attacked *A. senatoria* life stages and Arnaud (1978) reported 11 species of Tachinidae. Coffelt & Schultz (1990c) reported three hymenopteran primary parasites, one dipteran tachinid parasite, and four hymenopteran hyperparasites from *A. senatoria* in southeastern VA.

Several diseases were reported from *A. senatoria* larvae and pupae. Hitchcock (1961c) found *Cordyceps militaris* (Fr.) Link killed 14% of the pupae. Wallis (1959) identified a cytoplasmic polyhedrosis virus from diseased *A. senatoria* pupae. Kaya (1977) reported a nuclear polyhedrosis virus (NPV), that was originally isolated from *Autographa californica* (Speyer) (Lepidoptera: Noctuidae), alfalfa looper,

caused 30% mortality to *A. senatoria* larvae in the laboratory. A microsporidian, *Pleistophora schubergi* Zwolfer, caused high mortality to first-fourth instar *A. senatoria* in the laboratory (Kaya 1973). In the field, *P. schubergi* infested from 72-96% second and third instar *A. senatoria* (Kaya 1975).

Research Objectives

Anisota senatoria has become a major pest of *Quercus* species in southeastern VA. Insecticidal applications based on citizen complaints have not been effective and add significant pesticide load to the urban environment. Alternative control methods that emphasize IPM strategies have not been examined and efforts have not been made to understand the relationship between *A. senatoria* ecology, behavior, impact and host aesthetics. Four studies have been identified as part of this research. The objectives of each study are listed below and results of these studies are presented in the following 11 chapters.

A). An examination of the ecology of *A. senatoria* in the urban environment.

1) A study of the within-tree distribution and dispersion indices of the orangestriped oakworm (Lepidoptera: Saturniidae) with a fixed level precision sampling plan (**Chapter 2**).

2) A study of the influence of a tree growth regulator on orangestriped oakworm development and survival (**Chapter 3**).

3) A study of biological characteristics of the orangestriped oakworm in southeastern Virginia (**Chapter 4**).

B). An examination of *A. senatoria* larval aggregation behavior.

4) A study of the effects of group size on orangestriped oakworm survivorship reared in the laboratory and field (**Chapter 5**).

C). An examination of *A. senatoria* defoliation and frass impact.

5) A study of the impact of late season orangestriped oakworm defoliation on oak tree growth and vigor (**Chapter 6**).

6) A study of the relationship between orangestriped oakworm frass and instar, host plant and defoliation (**Chapter 7**).

D). Development of *A. senatoria* integrated pest management strategies.

7) A study of parasitism of orangestriped oakworm life stages in the urban landscape (**Chapter 8**).

8) A study of host plant preference of the orangestriped oakworm (**Chapter 9**).

9) A study on the development of an aesthetic injury level to decrease pesticide use against orangestriped oakworm (Lepidoptera: Saturniidae) in an urban pest management project (**Chapter 10**).

10) A study on quantification of an aesthetic injury level and threshold for an orangestriped oakworm urban pest management program (**Chapter 11**).

11) A study of citizen attitudes toward orangestriped oakworm: impact, control, host aesthetics, and IPM practices (**Chapter 12**).

Chapter 2

Within-tree distribution and dispersion indices for the orangestriped oakworm (Lepidoptera: Saturniidae) with a fixed level precision sampling plan

Introduction

Outbreaks of *Anisota senatoria* (J. E. Smith) (orangestriped oakworm), have become severe in some urban areas of Virginia leading to the development of integrated pest management (IPM) strategies (Coffelt & Schultz 1990b). However, lack of information on *A. senatoria* distribution and dispersion within *Quercus* (oak) trees has hindered development of sampling plans. The dispersion of a population, or the distribution pattern of organisms in space, has considerable ecological significance (Southwood 1978). Knowledge of insect spatial distributions is critical for development of viable sampling methods (Taylor 1984). The within-tree and within-plant distribution of numerous insects have been determined (Hall & Wilson 1974, Ohmart 1979, Larsson 1985, Cook & Hain 1989, Weakley et al. 1990) and sampling plans have been established from these data (Jones & Parrella 1984, Zehnder & Trumble 1985, Zehnder & Linduska 1988, Pena & Baranowski 1990). Green (1970) and Kuno (1969) described a sampling plan that estimates the mean density of an insect population relative to a fixed level of precision and provides a reliable estimate of the population mean. Myers (1978) and Mollet et al. (1984) discussed the advantages and disadvantages of various dispersion indices.

The objectives of this study were to compare spatial distribution patterns within trees of *A. senatoria* life stages

over several years to establish a sampling plan for *A. senatoria* IPM programs.

Materials and Methods

Quercus palustris Muench., pin oaks, planted along residential streets in Norfolk, VA, were chosen for this study. Trees were standardized by selecting trees those with similar height, diameter at breast height (dbh), growth condition and vigor, and crown development. Trees were also selected based on similar *A. senatoria* densities to ensure that populations were present for sampling. In 1987, 15 trees were initially sampled for eggs and 27 trees for early and late instars. In 1988 and 1989, 25 and 33 trees were initially sampled. The same trees were sampled throughout the study (1987-1989), unless trees were sprayed with insecticides, severely pruned, removed, or low *A. senatoria* populations existed. If necessary, replacement trees that had similar characteristics were used. Populations of *A. senatoria* tend to be localized and occur at the same locations annually, but populations fluctuate (Hitchcock 1958). The *Quercus palustris* trees sampled (n=33) were consistent in dbh (18.7$\pm$0.6 cm) and height (7.5$\pm$0.1 m), as indicated by the low standard error (mean$\pm$SEM).

The terminal 30 cm of a branchlet, a smaller division of a main branch (Dirr 1983), was chosen as the sampling unit. Trees were divided into a low, middle and high strata by

counting the number of branches from the main trunk and dividing by three. Low strata were 1.7-3.6 m above ground, middle strata were 3.7-5.5 m, and high strata were 5.6-7.6 m. Strata boundaries were marked with ribbon to aid sampling. On each sample date, 24 sample units were randomly chosen per stratum and a visual observation was made of the numbers of each *A. senatoria* life stage per sample unit. Sampling was initiated at the tree canopy drip line by an individual who walked around the tree periphery until all 24 samples were taken. *Anisota senatoria* life stages were easily observed in low and middle strata and sampling was aided by using a 1.8 m ladder for high strata.

Life stages recorded were eggs and first through fifth instars. These stages were easily recognized by their color and size. Eggs were large and measured 1.2 mm in diameter (Riotte & Peigler 1981), and were bright yellow. Eggs were oviposited on leaf undersides in masses of 200-700 (Hitchcock 1958) and the number of eggs per mass was estimated to the nearest 25 by determining the area covered on a typical *Q. palustris* leaf. Both first and second instars were yellow-green and gregarious (Hitchcock 1958, Riotte & Peigler 1981) and were combined as early instars for data analysis. The number of early instars were estimated by the same method used for eggs. Third instars developed yellow stripes and black color (Hitchcock 1958) and were not as gregarious. Third

instars were analyzed separately because they began to disperse out of the gregarious groups and migrate up the tree canopy, regardless of the amount of defoliation (unpublished data). Fourth and fifth instars were dark black with eight yellow-orange stripes and were 4-5 cm in length (Riotte & Peigler 1981), were not gregarious, and were estimated at similar densities per sampling unit; therefore, they were combined as late instars for data analysis. The number of third and late instars were counted per sampling unit and recorded.

Sampling was done by the same individual within 36 hours during each sampling period. In 1987, trees were sampled on July 16-17, August 5-6 and August 26-27. In 1988, trees were sampled weekly on July 19-20, July 26-27, August 2-3, August 8-9, August 15-16 and August 22-23. In 1989, trees were sampled weekly on July 31-August 1, August 7-8, August 13-14, August 17-18 and August 23-24.

Statistical Analysis. Means and variances of counts were calculated by stratum, replicate, and life stage for each date and year. Means and standard errors (SEM) were generated by SAS (SAS Institute, 1985) and the mean number of *A. senatoria* between strata were compared using a *t* test; comparison among three strata were conducted with Student-Newman-Keuls test (SAS Institute 1985). Dispersion indices were calculated using Taylor's power law (Taylor 1961) and Iwao's patchiness

regression (Iwao 1968).

Taylor's power law is a simple and useful description of species distribution (Southwood 1978) and relates variance (s^2) to mean density ($\bar{x}$) by the linear regression equation $\log s^2 = b\log\bar{x} + \log a$. The slope ($b$) is a species-specific measure of aggregation. Values of $b > 1$ indicate an aggregated or clumped distribution, and high values of b show strong aggregation (Southwood 1978). Values of $b = 1$ indicate a random (Poisson) distribution, and $b < 1$ indicate a regular distribution. The intercept (a) is a scaling factor related to sample size.

Iwao's patchiness regression is the regression of mean crowding (m^*) on the mean ($\bar{x}$) and is described by the regression model $m^* = \alpha + \beta\bar{x}$, where $m^* = \bar{x} + [s^2/\bar{x} - 1]$ (Lloyd 1967). The slope (β) is a density contagiousness coefficient and is related to the pattern in which an organism utilizes its habitat (Southwood 1978). Values of $\beta > 1$ indicate a clumped population, $\beta = 1$ a random (Poisson) distribution, and values of $\beta < 1$ are undefined (Iwao 1968). The intercept or alpha (α) is a measure of crowding and contagion. A negative value of α shows a tendency for organisms to repel each other (Southwood 1978).

The Proc REG procedure of SAS (SAS Institute 1985) was

used to generate regression statistics and pairwise comparisons of regression slopes were conducted using the Student's *t* test (Gomez & Gomez 1984). If *A. senatoria* life stages were present on less than 33% of the trees sampled, then dispersion parameters were not reported due to inflated slope coefficients (*b* values > 1,500). Within each year, Taylor's slope coefficients were, in most cases, significantly different ($P<0.05$) among life stages, dates, and strata. Therefore, a common regression equation was not fitted to pooled data (Gomez & Gomez 1984).

The required number of *Quercus* samples at various *A. senatoria* egg and early instar densities were calculated by rearrangement of Green's (1970) formula (Finch et al. 1975):

$$\log n = (\log a - 2\log D_0) - (2-b)\log \bar{x} \quad (1)$$

where a and b are Taylor's intercept and slope values respectively, n is the sample size, and D_0 is the fixed level of precision. Estimates of population densities within 25% of the mean are sufficiently accurate for pest management programs (Southwood 1978). Therefore, precision levels were set at 0.20, 0.25, and 0.30.

Results and Discussion

Within-tree distribution. Means for high strata were not reported if *A. senatoria* life stages were not present or if only one tree had stages present. Means of *A. senatoria*

counts for each of three strata provided information on the reliability of each stratum as a potential sampling location (Tables 1-3). In 1987 and 1988, there were significantly more eggs in low strata compared with middle strata (Table 1 & 2). Eggs were not found in high strata in 1988; therefore, high strata were not sampled in 1989. The presence of eggs primarily in low strata revealed the oviposition behavior of *A. senatoria* females. Gravid *A. senatoria* females were poor fliers and crawled up tree trunks and oviposited eggs on the first available lower branches (Hitchcock 1958, 1961a).

Significantly more early instars were sampled in low strata compared with middle or high strata across all dates and years (Tables 1-3). The presence of early instars primarily in the low strata revealed *A. senatoria* gregarious behavior. Hitchcock (1958) reported early instars were gregarious and existed in clumped distributions upon egg eclosion.

Sampling dates in 1987 were separated by three weeks (Table 1). Therefore, few third instars were observed and counts were not recorded. Large numbers of third instars first appeared on August 7-9, 1988-1989 (Tables 2 & 3). Significantly more third instars were sampled in low and middle strata compared with high strata (Tables 2 & 3).

Late instars first appeared on August 7-9, 1988-1989 (Tables 2 & 3). Significantly more late instars were sampled

in middle strata compared with low and high strata on August 17-18 and August 23-24, 1989 (Table 3). However, on most sample dates in 1987-1989, late instar densities were not significantly different among low, middle and high strata (Tables 1-3). This was attributed to the behavior of late instars. Late instars initially moved upward in the tree for continued feeding, and later migrated down and off the tree in search of pupation sites in soil litter beneath the tree. Observations from 1987-1989 indicated that distribution patterns of *A. senatoria* life stages were similar in trees regardless of the amount of defoliation that occurred.

Although *A. senatoria* populations were localized and occurred in the same locations each year, large population fluctuations occurred between years. Hitchcock (1958, 1961a) reported an outbreak of *A. senatoria* in 1958 which resulted in over 15,000 ha of trees defoliated, but by 1960 only 10.5 ha were defoliated. According to Norfolk Bureau of Parks and Forestry officials and personal observations (unpublished data), a peak in *A. senatoria* populations occurred in 1986 in Norfolk, VA. Populations declined in 1987 (unpublished data). The mean number of eggs in the low strata on July 16-17 was 88.1. *Anisota senatoria* populations increased in 1988 compared with 1987, as indicated by the larger mean number of eggs in low strata (Table 2). Data were not available for the mean number of eggs in 1989 (Table 3); however, there were larger

numbers of larvae on similar sampling dates in 1989 compared with 1987 and 1988 (Tables 1-3). These data and observations indicated *A. senatoria* populations varied between the three years of this study. Weather conditions may have contributed to the population fluctuations between years. The 11 year (1980-1990) monthly average precipitation for Norfolk, VA was 11.1 cm; average precipitation was 8.0 cm in 1987, 9.8 cm in 1988 and 15.5 cm in 1989. Average precipitation increased from 1987 to 1989, and the dry conditions in 1987 may have resulted in lower *A. senatoria* populations compared with other years. Houser (1931) reported that the severe drought of 1930 significantly reduced *A. senatoria* populations in Ohio.

Dispersion indices. Taylor's power law and Iwao's patchiness regression were generated from *A. senatoria* 1987-1989 data (Tables 4-8). Comparisons between dispersion models that had higher coefficient of determination (R^2) values provided the best fit of count data to the regression equation (Zehnder & Linduska 1988, Jones & Parrella 1984, Pena & Baranowski 1990). Taylor's regression generated higher R^2 values (Tables 4, 5 & 7) and indicated this method provided a better fit to the count data. Therefore, Taylor's parameters were used for comparison of aggregation between stages and for estimating the mean density relative to a fixed level of precision.

Taylor's slope coefficients were significantly different ($P<0.05$) among years for all life stages. This was attributed to the previously discussed *A. senatoria* population fluctuations between years. Taylor's power law significantly ($P<0.01$) accounted for variation in all *A. senatoria* stages, strata, dates, and years (Tables 4, 5 & 7). The only exception was early instars in low strata on July 26-27, 1988, where $P>0.10$ (Table 5). Taylor's method significantly accounted for variation at $P<0.10$ for late instars in high strata on August 15-16, 1988 (Table 5).

Taylor's regression generated slope values greater than 1.0 for all stages, dates, strata, and years (Tables 4, 5 & 7). This indicated all *A. senatoria* life stages were clumped or aggregated. The higher the value of b, the stronger the aggregation (Southwood 1978). Taylor's slope coefficients in low strata during August 8-9 and 15-16, 1988 (Table 5); August 13-14, 1989 (Table 7), and middle strata during August 7-8, 1989 (Table 7) indicated that aggregation was greatest among early instars, followed by third instars and late instars. Aggregation of third instars was greater compared with late instars (Tables 5 & 7). This was related to the variability in the amount of gregarious behavior among different life stages. Early instars were the most gregarious, followed by third instars and late instars.

In the first two sample dates of 1987 and 1988, Taylor's slope coefficient in low strata for eggs was not significantly different ($P>0.05$) compared with early instars; therefore, these data were combined (Tables 4 & 5). Knowledge of the distribution pattern of *A. senatoria* eggs and early instars was important when developing sampling programs. An aesthetic threshold was established based on the number of egg masses and aggregated early instars (Chapter 11), and an aesthetic injury level for treatment decisions was implemented (Coffelt & Schultz 1990b). Sampling for eggs and early instars to determine if aesthetic thresholds are reached will be a key component of *A. senatoria* IPM programs. Therefore, a technique is required that determines the minimum number of *Quercus* samples necessary to estimate egg and early instar densities, given a fixed level of precision.

One method was described by Zehnder & Linduska (1988). They determined the number of tomato plant samples needed to estimate the density of larval and adult *Leptinotarsa decemlineata* (Say) (Coleoptera: Chysomelidae), Colorado potato beetle. This method was applied to density estimates of *A. senatoria*. The sample size (n) for any given mean value ($\bar{x}$) is calculated based on Taylor's slope and intercept values inserted into equation (1) at the desired level of precision (Do). A line drawn from the mean number of eggs and early

instars per tree to the sample number curve gives the number of tree samples needed to estimate the population mean (Figure 1). The required number of samples shown in Figure 1 are based on data for low strata during July 19-20 and July 26-27, 1988 (Table 5). Sampling for eggs and early instars is recommended during July 15-31.

For example, at a mean density of 2,000 eggs and early instars per tree at the 0.25 precision level, 39 *Quercus* samples are required (Figure 1). More samples (61) are required at the 0.20 precision level and fewer samples (27) are required at the 0.30 precision level. As the *A. senatoria* densities increased, the required number of samples decreased. Zehnder & Linduska (1988) found a similar relationship for *L. decemlineata*. The mean densities of *A. senatoria* in Figure 1 were selected because the actual range of eggs and early instars per tree in 1988 was 400 to 10,000, and early instar counts from 1987-1989 were within this range. These data (Figure 1) were an accurate representation of *A. senatoria* densities and the required number of samples was realistic. During a 1988 IPM program, a larger number of trees was sampled (140) daily for *A. senatoria* life stages (Coffelt & Schultz 1990b).

Taylor's parameters for combined data in 1987 were not used in equation (1) because the slope coefficient value was too large and gave unrealistic values for n. Comparisons

between 1987 and 1988 were difficult because of different sampling periods. Counts of eggs and early instars in 1987 were separated by three weeks (Table 4) compared with one week for 1988 (Table 5). This later sampling period in 1987 included a higher proportion of early instars, the most aggregated stage, and combined slope values were larger compared with 1988. Jones & Parrella (1984) described a situation where certain regression parameters were not used in a sequential sampling equation because the equation yielded unrealistic negative values of insect numbers.

The distribution and dispersion of *A. senatoria* life stages among strata presented in this study has important application in shade tree IPM programs. Arborist and IPM scouts can monitor *A. senatoria* eggs and early instars and target pesticide sprays only in the lower strata, resulting in reduced pesticide volume. Additional benefits include less mortality of non-target parasites and predators and less pesticide drift in the urban landscape. The clumped distribution of all *A. senatoria* life stages will aid in monitoring and conducting counts. Related studies on establishing an aesthetic threshold (Chapter 11) and injury level (Chapter 10) complement these studies on sampling requirements for the estimation of egg and early instar densities, and will provide a framework for implementation of a comprehensive IPM program for *A. senatoria*.

Table 1. Distribution of *A. senatoria* in *Q. palustris*, 1987.

Stage	Sample Date	Stratum	Mean±SEM No. per branchlet[v]	N[w]
Egg	July 16-17	Low	88.1±9.8[x]	15
		Middle	8.6±2.5	15
Early Instars	Aug. 5-6	Low	52.7±6.5a[y]	27
		Middle	10.9±2.8b	27
		High	0.7±0.6c	27
Late Instars	Aug. 26-27	Low	1.8±0.3a	25
		Middle	2.3±0.3a	25
		High	1.5±0.2a	25

[v]Counts were transformed to logarithms before analysis.
[w]Number of *Q. palustris* replicates.
[x]Significant ($P<0.05$) *t* test.
[y]Means within columns followed by the same letter are not significantly ($P<0.05$) different for indicated dates (Student-Newman-Keuls test).

Table 2. Distribution of *A. senatoria* in *Q. palustris*, 1988.

Stage	Sample Date	Stratum	Mean±SEM No. per branchlet[v]	N[w]
Egg	July 19-20	Low	127.2±14.5[x]	25
		Middle	9.6±3.6	25
Early Instars	July 26-27	Low	76.4±8.2[x]	25
		Middle	5.7±2.3	25
Early Instars	Aug. 2-3	Low	62.1±7.1[x]	25
		Middle	2.5±1.3	25
Early Instars	Aug. 8-9	Low	20.1±2.9[x]	25
		Middle	1.5±0.8	25
3rd Instars		Low	5.7±1.0[x]	25
		Middle	1.1±0.4	25
Late Instars		Low	1.2±0.2a[y]	25
		Middle	1.1±0.2a	25
		High	0.4±0.1a	25
Early Instars	Aug. 15-16	Low	5.7±1.5[x]	25
		Middle	0.4±0.3	25
3rd Instars		Low	4.4±1.2a	25
		Middle	2.1±0.6ab	25
		High	0.5±0.3b	25
Late Instars		Low	1.2±0.2a	25
		Middle	1.1±0.2a	25
		High	0.4±0.1a	25
3rd Instars	Aug. 22-23	Low	2.2±0.8[z]	20
		Middle	1.2±0.6	20
Late Instars		Low	1.9±0.4a	20
		Middle	2.1±0.4a	20
		High	1.9±0.5a	20

[v]Counts were transformed to logarithms before analysis.
[w]Number of *Q. palustris* replicates.
[x]Significant ($P<0.05$) for indicated dates, *t* test.
[y]Means within columns followed by the same letter are not significantly ($P<0.05$) different for indicated dates (Student-Newman-Keuls test).
[z]Nonsignificant ($P>0.05$) *t* test.

Table 3. Distribution of *A. senatoria* in *Q. palustris*, 1989.

Stage	Sample Date	Stratum	Mean±SEM No. per branchlet[v]	N[w]
Early Instars	July 31-Aug. 1	Low	87.0±7.9[x]	33
		Middle	16.8±4.7	33
3rd Instars		Low	1.7±0.5[z]	33
		Middle	1.2±0.7	33
Early Instars	Aug. 7-8	Low	26.2±3.6[x]	28
		Middle	5.1±1.4	28
3rd Instars		Low	6.4±1.2a[y]	28
		Middle	4.6±1.3a	28
		High	1.0±0.6b	28
Late Instars		Low	0.7±0.2a	28
		Middle	0.8±0.2a	28
		High	0.7±0.3a	28
Early Instars	Aug. 13-14	Low	6.3±2.1[z]	26
		Middle	2.4±1.1	26
3rd Instars		Low	7.1±1.2a	26
		Middle	6.8±1.1a	26
		High	1.2±0.4b	26
Late Instars		Low	1.1±0.2b	26
		Middle	2.5±0.4a	26
		High	1.3±0.4ab	26
3rd Instars	Aug. 17-18	Low	7.0±2.6a	23
		Middle	5.1±1.1a	23
		High	0.8±0.4b	23
Late Instars		Low	1.7±0.3b	23
		Middle	4.0±0.5a	23
		High	2.1±0.7b	23
Late Instars	Aug. 23-24	Low	1.4±0.4c	23
		Middle	4.1±0.6a	23
		High	2.4±0.6b	23

[v]Counts were transformed to logarithms before analysis.
[w]Number of *Q. palustris* replicates.
[x]Significant ($P<0.05$) for indicated dates, *t* test.
[y]Means within columns followed by the same letter are not significantly ($P<0.05$) different for indicated dates (Student-Newman-Keuls test).
[z]Nonsignificant ($P>0.05$) for indicated dates, *t* test.

Table 4. Regression statistics generated by Taylor's power law and Iwao's patchiness regression for counts of *A. senatoria*, 1987.

Taylor's power law[x]

Stage	Sample Date	Stratum	N[z]	Log *a*	*b*±SEM	R^2	*P*
Egg	July 16-17	Low	15	2.2	12.9±1.4	0.82	0.0001
Early Instars	Aug. 5-6	Low	27	1.9	15.2±1.2	0.86	0.0001
		Middle	27	0.3	374.0±1.4	0.93	0.0001
Late Instars	Aug. 26-27	Low	25	0.6	54.3±1.3	0.88	0.0001
		Middle	25	0.4	166.9±1.6	0.82	0.0001
		High	25	0.5	37.6±1.4	0.81	0.0001

Iwao's patchiness regression[y]

Stage	Sample Date	Stratum	N[z]	alpha	*B*±SEM	R^2	*P*
Egg	July 16-17	Low	15	297.7	0.9±0.5	0.20	0.0900
Early Instars	Aug. 5-6	Low	27	126.8	1.7±0.2	0.60	0.0001
		Middle	27	37.1	5.8±0.6	0.77	0.0001
Late Instars	Aug. 26-27	Low	25	-0.8	5.2±0.8	0.65	0.0001
		Middle	25	-3.2	6.0±1.1	0.53	0.0001
		High	25	0.2	3.0±0.4	0.65	0.0001

[x]equation: $\log s^2 = b \log x + \log a$.
[y]equation: $m^* = \text{alpha} + Bx$.
[z]Number of mean and variance pairs used to calculate regression statistics.

Table 5. Regression statistics generated by Taylor's power law for counts of *A. senatoria*, 1988.

Stage	Sample Date	Stratum	N[z]	Taylor's power law[y] Log *a*	*b*±SEM	R^2	*P*
Egg	July 19-20	Low	25	3.8	2.2±1.2	0.41	0.0006
Early Instars	July 26-27	Low	25	3.7	1.8±1.4	0.10	0.1143
Early Instars	Aug. 2-3	Low	25	2.0	17.4±1.2	0.90	0.0001
Early Instars	Aug. 8-9	Low	25	0.6	155.9±1.5	0.86	0.0001
3rd Instars		Low	25	0.7	101.1±1.6	0.80	0.0001
Late Instars		Low	25	0.3	12.0±1.6	0.51	0.0001
Early Instars	Aug. 15-16	Low	25	0.8	664.7±1.3	0.95	0.0001
3rd Instars		Low	25	0.6	103.8±1.6	0.78	0.0001
		Middle	25	0.5	342.8±2.1	0.72	0.0001
Late Instars		Low	25	0.6	36.2±1.4	0.78	0.0001
		Middle	25	0.4	83.5±2.1	0.61	0.0001
		High	25	0.3	13.9±4.1	0.13	0.0771
3rd Late Instars	Aug. 22-23	Low	20	0.1	814.1±1.5	0.93	0.0001
		Low	20	0.7	33.5±1.4	0.82	0.0001
		Middle	20	0.5	37.2±1.5	0.82	0.0001
		High	20	0.3	53.2±1.7	0.74	0.0001

[y]equation: $\log s^2 = b \log x + \log a$.
[z]Number of mean and variance pairs used to calculate regression statistics.

Table 6. Regression statistics generated by Iwao's patchiness regression for counts of *A. senatoria*, 1988.

Stage	Sample Date	Stratum	N[z]	Iwao's patchiness regression[y] alpha	*B*±SEM	R^2	*P*
Egg	July 19-20	Low	25	468.4	-0.2±0.1	0.09	0.1280
Early Instars	July 26-27	Low	25	385.1	0.4±0.2	0.10	0.1343
Early Instars	Aug. 2-3	Low	25	263.4	1.6±0.5	0.30	0.0042
Early Instars	Aug. 8-9	Low	25	105.1	3.6±1.0	0.33	0.0026
3rd Instars		Low	25	17.9	3.2±0.6	0.49	0.0001
Late Instars		Low	25	0.4	8.4±0.7	0.85	0.0001
Early Instars	Aug. 15-16	Low	25	13.3	8.1±1.0	0.73	0.0001
3rd		Low	25	25.5	3.3±2.4	0.07	0.1945
Instars		Middle	25	7.9	5.6±0.7	0.68	0.0001
Late		Low	25	1.6	3.7±0.6	0.60	0.0001
Instars		Middle	25	0.4	4.6±0.4	0.79	0.0001
		High	25	-0.2	7.3±1.8	0.40	0.0008
3rd	Aug. 22-23	Low	20	1.2	7.7±0.5	0.92	0.0001
Late		Low	20	1.2	3.9±0.7	0.62	0.0001
Instars		Middle	20	1.5	2.9±0.6	0.57	0.0001
		High	20	0.8	2.7±0.3	0.78	0.0001

[y]equation: $m^* = \text{alpha} + Bx$.
[z]Number of mean and variance pairs used to calculate regression statistics.

Table 7. Regression statistics generated by Taylor's power law for counts of *A. senatoria*, 1989.

Stage	Sample Date	Stratum	N[z]	Taylor's power law[y] Log *a*	*b*±SEM	R^2	*P*
Early Instars	July 31-Aug. 1	Low	33	2.6	7.4±1.2	0.79	0.0001
		Middle	33	0.05	375.3±1.1	0.97	0.0001
Early Instars 3rd Instars Late Instars	Aug. 7-8	Low	28	0.5	148.5±1.4	0.89	0.0001
		Middle	28	0.1	1299.7±1.4	0.93	0.0001
		Low	28	0.9	54.0±1.5	0.77	0.0001
		Middle	28	0.4	286.8±1.7	0.81	0.0001
		Low	28	0.3	133.0±2.1	0.60	0.0001
		Middle	28	0.4	34.0±2.1	0.44	0.0001
		High	28	0.3	33.2±1.5	0.71	0.0001
Early 3rd Instars Late Instars	Aug. 13-14	Low	26	0.1	544.2±1.3	0.94	0.0001
		Low	26	0.5	124.7±1.5	0.85	0.0001
		Middle	26	0.7	80.9±1.7	0.73	0.0001
		Low	26	0.6	36.9±1.3	0.85	0.0001
		Middle	26	0.6	26.7±1.4	0.76	0.0001
		High	26	0.3	52.1±1.6	0.74	0.0001
3rd Instars Late Instars	Aug. 17-18	Low	23	0.4	139.5±1.5	0.84	0.0001
		Middle	23	0.4	208.9±1.7	0.82	0.0001
		Low	23	0.7	15.0±1.7	0.52	0.0001
		Middle	23	0.4	38.1±1.4	0.83	0.0001
		High	23	0.2	86.3±1.7	0.76	0.0001
Late Instars	Aug. 23-24	Low	17	0.6	36.7±1.3	0.92	0.0001
		Middle	17	0.3	40.8±1.4	0.85	0.0001
		High	17	0.3	32.0±1.4	0.86	0.0001

[y]equation: $\log s^2 = b \log x + \log a$.
[z]Number of mean and variance pairs used to calculate regression statistics.

Table 8. Regression statistics generated by Iwao's patchiness regression for counts of *A. senatoria*, 1989.

Stage	Sample Date	Stratum	N[z]	Iwao's patchiness regression[y] alpha	*B*±SEM	R^2	*P*
Early Instars	July 31-Aug. 1	Low	33	319.8	0.4±0.2	0.09	0.0744
		Middle	33	63.7	5.5±0.8	0.57	0.0001
Early Instars	Aug. 7-8	Low	28	106.6	2.2±0.8	0.21	0.0140
		Middle	28	42.9	8.0±1.6	0.48	0.0001
3rd Instars		Low	28	29.5	2.0±0.5	0.31	0.0019
		Middle	28	25.4	2.2±0.7	0.24	0.0074
Late Instars		Low	28	1.3	5.4±0.7	0.64	0.0001
		Middle	28	2.3	3.3±0.6	0.53	0.0001
		High	28	0.4	4.2±0.3	0.83	0.0001
Early	Aug. 13-14	Low	26	24.0	6.3±0.9	0.62	0.0001
3rd Instars		Low	26	17.0	2.6±0.5	0.52	0.0001
		Middle	26	28.7	1.7±0.8	0.15	0.0486
Late Instars		Low	26	0.9	5.3±0.7	0.69	0.0001
		Middle	26	5.1	1.5±0.4	0.37	0.0010
		High	26	0.7	2.3±0.1	0.92	0.0001
3rd Instars	Aug. 17-18	Low	23	19.5	1.5±0.3	0.49	0.0002
		Middle	23	19.6	2.5±0.8	0.28	0.0082
Late Instars		Low	23	5.1	1.6±0.6	0.22	0.0223
		Middle	23	0.8	2.0±0.3	0.61	0.0001
		High	23	2.0	1.8±0.3	0.70	0.0001
Late Instars	Aug. 23-24	Low	17	2.7	1.5±0.5	0.34	0.0139
		Middle	17	0.9	1.8±0.2	0.76	0.0001
		High	17	0.3	2.0±0.2	0.82	0.0001

[y]equation: $m^* = \text{alpha} + Bx$.
[z]Number of mean and variance pairs used to calculate regression statistics.

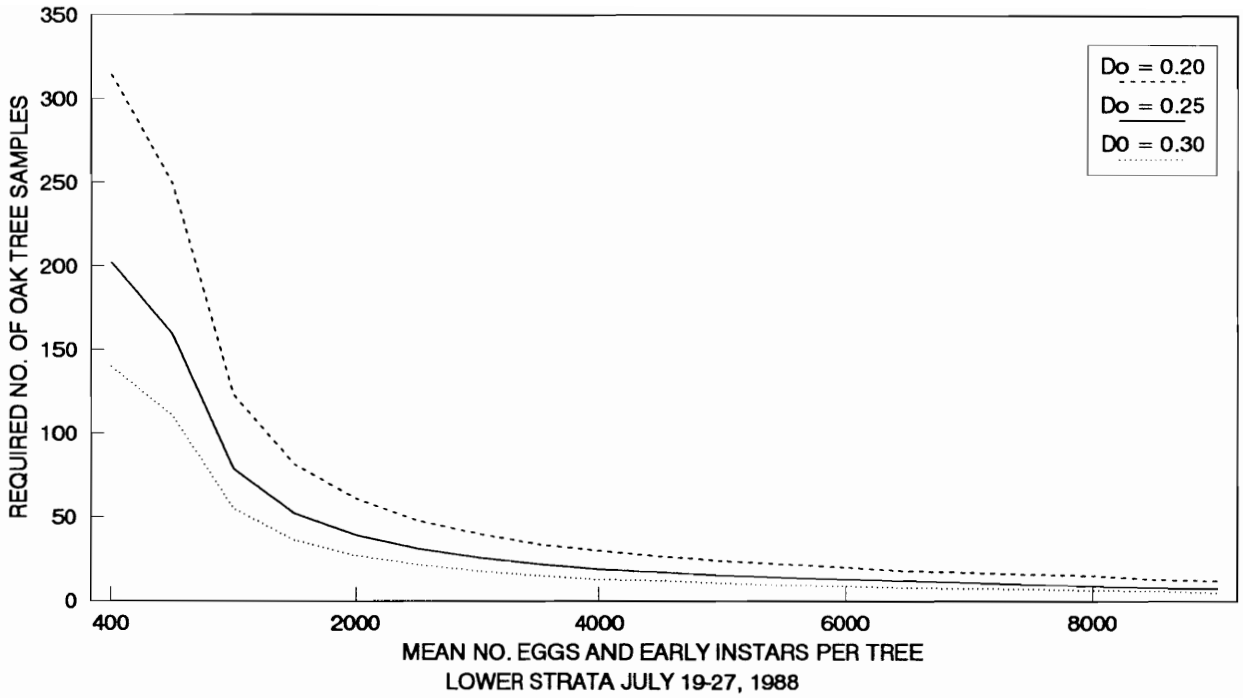

Figure 1. Required number of *Quercus* samples for *A. senatoria* eggs and early instars at the 0.20, 0.25 and 0.30 levels of precision (*Do*).

Chapter 3

Influence of a tree growth regulator on orangestriped oakworm development and survival

Introduction

Tree growth regulators (TGRs) are organic compounds (other than nutrients) that promote, inhibit, or otherwise modify specific plant physiological processes (Weaver 1972). They are applied to woody plants to reduce growth, extend trimming cycles, and reduce pruning and maintenance expenses (Watson 1987a, 1987b). Additional benefits include enhanced tree beauty through darker green foliage and improved stress resistance (Watson 1987a). Application of TGRs includes the widespread use of trunk injection (Perry et al. 1991, Stipes 1988), soil treatment, bark banding and foliar sprays.

Tree growth regulators are categorized as inhibitors of terminal buds or subapical meristematic tissues (Sachs et al. 1986). Terminal bud inhibitors are primarily hormonal (Miller & Abbott 1991), an example is dikegulac which reduces tree growth but may be phytotoxic (Wright & Moran 1988a, 1988b). Subapical meristematic inhibitors or antigibberellic compounds disrupt gibberellin biosynthesis, slow cell elongation, compress internodes, and move upward in the xylem (Kimball 1990, Miller & Abbott 1991). Examples include paclobutrazol, flurprimidol, and uniconazole. Paclobutrazol is the most extensively used TGR (Miller & Abbott 1991) and is formulated with methanol as the solvent.

The influence of various plant growth regulators on arthropods with piercing-sucking mouthparts such as mites,

aphids, whiteflies, and azalea lace bugs has been demonstrated in previous studies (Rodriquez & Campbell 1961, Honeyborne 1969, Fischer & Shanks 1979, Eichmeier & Guyer 1960, Coffelt & Schultz 1988). These effects included decreased fecundity, development and survival and a reduction in infestations. However, the effect of TGRs on arthropod development and survival has not been examined.

The objectives of this study were to determine the effect of paclobutrazol on the development and survival of *Anisota senatoria*, orangestriped oakworm, in the laboratory and in the field.

Materials and Methods

Twelve *Quercus phellos* L., willow oaks, approximately 8 years old planted at the Hampton Roads Agricultural Experiment Station (HRAES), Virginia Beach, VA were selected for this study. A completely randomized design was used with three tree replicates of each treatment. Trees were similar in diameter at breast height (8.3±0.5 cm dbh), height, and overall tree health. Tree trunks were injected according to standard procedures (Watson 1987b). Paclobutrazol 20 UL has the chemical name (±)-(R^*,R^*)-*B*-[(4-chlorophenyl)methyl)]-*a*-(1,1-dimethylethyl)-1H-1,2,4-triazole-1-ethanol. Paclobutrazol trunk injection was made on June 20, 1988, utilizing an Arborchem three point injector (Asplundh Tree Expert Co.,

Willow Grove, PA). A 10.2 cm hole spacing was used and holes were drilled 5.0 cm into the trunk at a 45° angle, 30 cm above ground. There were four treatments. Paclobutrazol was applied with methanol as a solvent. Treatments were 40 (recommended rate), 80, and 160 ml per injection hole or 0.2 g (AI)/diameter-cm, 0.4 g (AI)/diameter-cm, and 0.8 g (AI)/diameter-cm, respectively. Untreated control trees received 40 ml of methanol per injection hole on June 21, 1988.

1988-1991 *Q. phellos* **growth measurements.** The influence of paclobutrazol on tree growth was determined by measuring tree height, new growth terminals, leaf nutrients, shoot buds, and leaf area. In June of each year, 1988-1991, tree height was estimated using a 6.5 m pole marked at 0.1 m increments. One individual held the pole next to the tree trunk and another individual stood approximately 5 m away from the tree and estimated the height. The difference in tree height between years (top growth) was calculated. In June of each year, 1988-1991, ten randomly selected new growth terminals were selected from the lower canopy of each tree, 1-3 m above ground, and the terminal length was measured. In June of each year, 1988-1990, new growth on three terminals in the upper canopy, >3 m above ground, was measured. Terminals were pruned and the location marked with ribbon so growth could be

measured from the same location each year. By 1991, ribbons were lost and data were not taken in the upper canopy. In August, 1988, five leaves were randomly removed from the control treatment and the paclobutrazol treatment at the highest rate, and sent to VPI & SU soil testing and plant analysis laboratory for macronutrient and micronutrient analysis. In April of each year, 1989-1990, four shoots per tree were selected and the number of expanded and unexpanded buds counted, and the length of expanded buds measured. In this study, shoots were equivalent to a 10 cm section of the previous year's growth. In May of each year, 1989-1991, four leaves per tree were collected, pressed, and leaf area measured using a video analysis device (Skye Instruments, Quakertown, PA). This device was described by Hough-Goldstein et al. (1991).

A. senatoria **experiments. 1989-1990 laboratory experiments.** In July 1989 and 1990 laboratory studies, 5 and 10 randomly selected cuttings were pruned from the control treatment and paclobutrazol treatments and placed in 100 ml water-filled cups. Cups were placed in 19 x 11 cm plastic boxes that had two 3.2 cm ventilation holes covered with organdy cloth. Boxes were placed in an environmental chamber maintained at 27°C (L) and 22°C (D) and a photoperiod of 16:8 (L:D). *Anisota senatoria* eggs were pinned on cuttings and

five larvae per cutting were allowed to develop. Cuttings were replaced as needed. Larvae were examined daily and the date of 60% larval molting to the next instar and the number of live larvae were recorded. Larvae were reared from first instar to prepupae. Prepupae were placed in laboratory boxes filled with soil and allowed to pupate. Development time and survival in each stage was determined. Male and female pupae were sexed according to characters described by Ehrlich et al. (1969) and weighed to the nearest 0.01 g with a Mettler AE50 balance (Mettler Instruments, Hightstown, NJ).

1989-1990 field experiments. In July 1989, one *A. senatoria* egg mass was pinned on a leaf of the control treatment and each of the paclobutrazol treatments. Larvae were checked every 7-10 days. In July 1990, *A. senatoria* eggs were pinned on leaves and five larvae allowed to develop enclosed in a 46 x 10.2 cm organdy sleeve cage placed over a 30 cm *Q. phellos* terminal. Two sleeve cages were used per tree. Larvae were checked every 5-7 days. In 1989 and 1990, development time and percent survival from first instar to the pupal stage were determined. Percent survival was based on the number of live larvae entering each stage. Prepupae were placed in laboratory boxes filled with soil and allowed to pupate. Pupal sex and weight were determined as previously described.

Data were subjected to analysis of variance (ANOVA) (SAS

Institute 1985) and differences between three or more treatment means were tested for significance ($P<0.05$) with Student-Newman-Keuls test (SAS Institute 1985). Arcsin transformation was performed on percent survival data to maintain homogeneity of variance (Steel & Torrie 1980).

Results and Discussion

1988-1991 *Q. phellos* growth measurements. Paclobutrazol significantly reduced growth of *Q. phellos* (Tables 1-3). The paclobutrazol treatment at the highest rate had decreased top growth one to three years posttreatment indicating this treatment severely retarded growth (Table 1). Differences in top growth were significantly higher in the control treatment one year posttreatment compared with paclobutrazol treatments. Top growth differences were nonsignificant between treatments two years posttreatment because of the high standard error associated with each mean (SEM). The control treatment had the most top growth and the paclobutrazol treatment at the highest rate had the least. Differences in top growth were significantly higher in the control treatment and the lowest rate of paclobutrazol three years posttreatment compared with the two highest rates of paclobutrazol.

Length of new growth terminals in both lower and upper canopies were not significantly different between treatments in the pretreatment period of 1988 and averaged 24 cm of growth (Table 2). In the lower canopy one and two years

posttreatment, new growth differences were significantly higher in the control treatment compared with paclobutrazol treatments. Differences in new growth were significantly higher in the control treatment and the lowest rate of paclobutrazol three years posttreatment compared with the two highest rates of paclobutrazol. In the upper canopy one year posttreatment, differences in new growth were significantly higher in the control treatment compared with paclobutrazol treatments. New growth differences were significantly higher in the control treatment and the lowest rate of paclobutrazol two years posttreatment compared with the two highest rates of paclobutrazol.

Differences in leaf area were significantly larger in the control treatment one year posttreatment compared with paclobutrazol treatments (Table 2). The paclobutrazol treatment at the highest rate had the smallest leaf area. There were significant differences in leaf area between all treatments two years posttreatment. Leaf area differences were significantly higher in the control treatment and the lowest rate of paclobutrazol three years posttreatment compared with the two highest rates of paclobutrazol.

Differences in the number of expanded buds were not significantly different between treatments one and two years posttreatment (Table 3). Differences in the length of expanded buds were not significantly different between

treatments one year posttreatment, but were significantly higher in the control treatment two years posttreatment compared with paclobutrazol treatments. Differences in the number of unexpanded buds were significantly higher in the paclobutrazol treatment at the highest rate one year posttreatment compared with the control, but were not significantly different in the two years posttreatment between the highest rate of paclobutrazol and the control. Although shoots were sampled in April of both years, observations indicated that bud break was late two years posttreatment for the paclobutrazol treatment at the highest rate, and differences were not detected.

Leaves were analyzed for macronutrients and micronutrients. Macronutrients included calcium, phosphorus, potassium, magnesium, and nitrogen. Micronutrients included aluminum, boron, copper, iron, and manganese. Macronutrients and micronutrients were not significantly different ($P>0.05$) in the control treatment two months posttreatment compared with the paclobutrazol treatment at the highest rate. Mean macronutrients were $0.90\pm0.3\%$ and $0.94\pm0.4\%$ and mean micronutrients were 55.6 ± 16.6 ppm and 64.6 ± 20.4 ppm, respectively. Because paclobutrazol is an antigibberellic compound, nutrient composition was unaffected.

These data indicated that paclobutrazol significantly reduced *Q. phellos* growth, especially one and two years

posttreatment. Data taken three years posttreatment indicated paclobutrazol activity had decreased, especially in the paclobutrazol treatment at the lowest rate. Kimball (1990) stated that the effect of TGRs was observed within several months to a year. Growth retardation by paclobutrazol has been reported to persist for three years posttreatment (Anonymous 1988).

A. senatoria **experiments. 1989-1990 laboratory experiments.** The paclobutrazol treatment at the highest rate significantly slowed development one year posttreatment for second and third instars compared with the control treatment (Table 4). The paclobutrazol treatment at the highest rate significantly decreased survival one year posttreatment for third instars compared with the control treatment (Table 5). There was a trend for the paclobutrazol treatment at the highest rate to decrease survival for second instars compared with the control treatment (Table 5). Feeding consumption data were not taken in this study. However, slower development probably occurred because of decreased feeding ability by early instar *A. senatoria* (second-third) on the smaller leaves resulting from the paclobutrazol treatment at the highest rate. The paclobutrazol treatment at the highest rate had a 95% reduction in leaf area one year posttreatment (Table 2) compared with control treatments, and leaves were extremely twisted and curled.

Late stages (fourth instar-prepupae) showed a different trend one year posttreatment compared with early instars (Tables 4 & 5). Paclobutrazol treatments significantly accelerated development one year posttreatment for fifth instars compared with the control treatment (Table 4). Paclobutrazol treatments at the two lower rates significantly increased survival for fourth instars compared with the paclobutrazol treatment at the highest rate (Table 5). Paclobutrazol treatments at the two lower rates significantly increased survival for fifth instars compared with the control and paclobutrazol treatment at the highest rate. The unusually low survival in the control for fourth and fifth instars cannot be explained biologically. The paclobutrazol treatment at the lowest rate significantly increased survival for prepupae compared with the paclobutrazol treatment at the highest rate. These data suggested an enhanced effect in later instars and the prepupal stage on paclobutrazol treatments at the two lowest rates. Late instars are not as gregarious compared with early instars and feed individually on leaves (Chapter 2). This behavior and possibly increased feeding on paclobutrazol treatments at the two lower rates accelerated development and enhanced survival.

Development of second-fifth instars and prepupae was not significantly different between all treatments two years posttreatment (Table 4). Percent survival by stage was not

significantly different between all treatments (Table 5). These data suggested that the influence of paclobutrazol on *A. senatoria* development and survival had decreased two years posttreatment, although paclobutrazol still influenced tree growth (Tables 1-3). Only development of first instars was influenced by paclobutrazol treatment two years posttreatment (Table 4), but survival was unaffected (Table 5). Paclobutrazol treatments at the two highest rates significantly accelerated development for first instars compared with control treatments and the lowest rate of paclobutrazol (Table 4). The accelerated development for first instars two years posttreatment was unexpected because no effect was measured one year posttreatment (Table 4). Although leaf chemistry was not measured in this study, differences may have appeared after two years and affected first instar development.

1989-1990 field experiments. Differences in development and survival from first instar to pupae were nonsignificant ($P>0.05$) between all treatments one and two years posttreatment, so data were combined (Table 6). Mean development from first instar to pupae on control treatments one and two years posttreatment was 34.2 days. Mean development from first instar to pupae was 31.7 ± 0.2 days one year posttreatment and 35.0 ± 0.3 days two years posttreatment.

Male pupal weights were not significantly diffferent

between all treatments in laboratory and field studies one and two years posttreatment. The paclobutrazol treatment at the lowest rate significantly increased female pupal weight in the laboratory one year posttreatment compared with the control treatment and the paclobutrazol treatment at the second lowest rate (Table 7). Paclobutrazol treatments at the two lower rates significantly increased female pupal weight in the field one year posttreatment compared with the control treatment and the paclobutrazol treatment at the highest rate. The control treatment had very low female pupal weights two years posttreatment compared with paclobutrazol treatments. Only five females were recovered from the control treatment in the field, and these data were a result of small sample size and were not significant biologically. Differences in female pupal weights were nonsignificant between all treatments in the laboratory two years posttreatment (data not shown).

Paclobutrazol significantly reduced *Q. phellos* growth and to a lesser extent *A. senatoria* development and survival. Plant growth regulators had the most significant effect on fecundity, development and survival of arthropods with piercing-sucking mouthparts (Honeyborne 1969, Coffelt & Schultz 1988). Insects with chewing mouthparts, such as *A. senatoria* larvae, may be less affected by tree growth regulators than insects with piercing-sucking mouthparts. The influence of tree growth regulators on insects with chewing

versus piercing-sucking mouthparts should be examined.

These data indicated that paclobutrazol significantly reduced *Q. phellos* growth, especially one and two years posttreatment. The most significant paclobutrazol effects on *A. senatoria* development and survival were measured one year posttreatment. Early and late instars differed in their response to paclobutrazol treatments. In laboratory studies one year posttreatment, the paclobutrazol treatment at the highest rate slowed development for second and third instars and decreased survival of third instars compared with control treatments. Paclobutrazol treatments at the two lower rates significantly increased survival for late instars and prepupae in the laboratory compared with the paclobutrazol treatment at the highest rate. Accelerated development occurred in the fifth instar with paclobutrazol treatments. Field development and survival was not affected by paclobutrazol treatments. The paclobutrazol treatment at the lowest rate significantly increased female pupal weight in the laboratory one year posttreatment. Paclobutrazol treatments at the two lower rates significantly increased female pupal weight in the field one year posttreatment. These data suggested that *Q. phellos* injected with paclobutrazol at the two lower rates may experience a more fit late instar population, as measured by increased survival, development, and female pupal weight. *Anisota senatoria* may be more adapted to feeding on these

trees one year posttreatment. Late instars compensated for changes in leaf morphology by increased feeding accompanied by increased *A. senatoria* fitness. Arborists that apply paclobutrazol to trees that contain *A. senatoria* populations should consider that increased fitness may result in more defoliation one year posttreatment. Trees that are highly susceptible to *A. senatoria* defoliation should not receive paclobutrazol treatments.

Table 1. Mean top growth in *Q. phellos* injected with paclobutrazol.

T[y]	Mean±SEM top growth (cm) 1 yr posttrt	2 yrs posttrt	3 yrs posttrt
C	98.0±16.8a[z]	111.3±39.7a	116.3±31.6a
X	34.6±16.2b	60.6±33.0a	96.5±32.0a
2X	23.1±16.9b	35.0±13.1a	10.3± 3.8b
4X	21.6± 3.8b	10.3± 3.8a	3.0± 3.0b

[y] Treatments C=control; Paclobutrazol rates X, 2X and 4X=40 ml, 80 ml and 160 ml per injection hole.
[z] Means within columns followed by the same letter are not significantly different (Student-Newman-Keuls test) (SAS Institute, 1985).
N=3 tree replicates.

Table 2. Mean length of new growth terminals in lower and upper canopies, and mean leaf area of *Q. phellos* injected with paclobutrazol.

Mean±SEM length of new growth terminals (cm)

Lower canopy[x]

T[y]	Year of Injection	1 yr posttrt	2 yrs posttrt	3 yrs posttrt
C	26.4±2.0a[z]	27.6±3.2a	42.2±3.8a	41.5± 0.8a
X	25.7±5.0a	2.6±0.6b	9.3±3.6b	33.9±10.9a
2X	22.1±1.4a	1.2±0.2b	2.3±0.4b	9.4± 0.5b
4X	24.0±3.0a	0.6±0.1b	0.8±0.2b	2.6± 1.3b

Upper canopy

C	27.7±4.8a	22.9±5.2a	45.6±5.9a	
X	29.1±7.0a	6.3±1.9b	12.6±2.0b	
2X	23.3±1.3a	2.0±0.3b	2.7±0.3c	
4X	28.5±2.7a	0.6±0.1b	0.8±0.1c	

Mean±SEM leaf area (mm^2)

	1 yr posttrt	2 yrs posttrt	3 yrs posttrt
C	551.1±71.2a	1228.3±66.5a	1281.5±156.0a
X	188.0±25.7b	827.3±97.6b	1027.1± 35.5a
2X	151.0±20.5bc	604.8±57.7c	897.5± 59.8b
4X	24.3±12.1c	369.0±22.2d	615.1± 85.9b

[x] Lower and upper canopy=1-3 m and >3 m above ground.
[y] Treatments C=control; Paclobutrazol rates X, 2X and 4X=40 ml, 80 ml and 160 ml per injection hole.
[z] Means within columns followed by the same letter are not significantly different (Student-Newman-Keuls test) (SAS Institute, 1985).
N=3 tree replicates.

Table 3. Mean number of expanded and unexpanded buds and length of expanded buds in *Q. phellos* injected with paclobutrazol.

Mean±SEM

	No. yrs posttrt	Treatment[y] C	X	2X	4X
No. expanded buds	1	8.9±0.8a[z]	7.8±0.3a	6.9±0.4a	4.4±2.2a
	2	7.2±0.1a	6.1±0.8a	8.5±0.3a	8.6±1.5a
Length (cm) expanded buds	1	5.0±1.3a	5.7±1.3a	3.1±0.2a	1.5±0.4a
	2	9.0±1.4a	2.9±1.5b	0.5±0.1b	0.3±0.05b
No. unexpanded buds	1	0.6±0.08b	4.0±0.3ab	3.4±0.7ab	5.6±2.1a
	2	0.0±0.0b	6.0±1.5a	3.9±1.2ab	1.9±0.3b

[y] Treatments C=control; Paclobutrazol rates X, 2X and 4X=40 ml, 80 ml and 160 ml per injection hole.
[z] Means within rows followed by the same letter are not significantly different (Student-Newman-Keuls test) (SAS Institute, 1985).
N=3 tree replicates.

Table 4. Influence of paclobutrazol treatments on the mean development of *A. senatoria* in the laboratory.

1 Year Posttrt. Mean±SEM development (days)

	STAGE					
T[x]	1st	2nd	3rd	4th	5th	PP[y]
C	7.3±0.2a[z]	6.7±0.1c	5.3±0.1b	6.0±0.4a	6.0±0.5a	3.1±0.1a
X	7.0±0.0a	7.1±0.1bc	5.8±0.1ab	5.5±0.1a	5.2±0.2b	3.2±0.2a
2X	7.4±0.1a	7.5±0.2ab	5.9±0.1ab	5.9±0.6a	5.4±0.3b	3.4±0.2a
4X	7.6±0.5a	7.9±0.1a	6.3±0.3a	5.8±0.2a	5.1±0.3b	2.7±0.2a

2 Years Posttrt. Mean±SEM development (days)

C	7.0±0.0a	6.8±0.8a	5.2±0.2a	5.2±0.2a	4.2±0.5a	3.8±0.2a
X	7.2±0.2a	6.4±0.2a	5.2±0.3a	5.0±0.0a	4.8±0.2a	3.2±0.3a
2X	6.4±0.2b	7.0±0.3a	5.6±0.2a	5.2±0.2a	5.2±0.3a	3.5±0.2a
4X	6.0±0.0b	7.2±1.2a	4.8±0.2a	4.8±0.2a	3.8±0.2a	3.0±0.4a

[x] Treatments C=control; Paclobutrazol rates X, 2X and 4X=40 ml, 80 ml and 160 ml per injection hole.
[y] PP=prepupal stage.
[z] Means within columns followed by the same letter are not significantly different (Student-Newman-Keuls test) (SAS Institute, 1985).
N=3 tree replicates.

Table 5. Influence of paclobutrazol treatments on the mean survival of *A. senatoria* in the laboratory.

Stage	Treatment[x] C	X	2X	4X
	1 Year Posttrt. Mean±SEM percent survival			
1st	96.0±4.0a[y]	94.0±4.2a	96.0±2.6a	94.0±3.0a
2nd	96.0±4.0a	96.0±4.0a	96.0±2.6a	84.0±5.8a
3rd	94.0±4.2a	90.0±5.3a	92.0±6.1a	68.0±8.5b
4th	72.0±8.0ab	88.0±6.1a	86.0±6.7a	56.0±9.8b
5th	62.0±8.1b	88.0±6.1a	86.0±6.7a	56.0±9.8b
PP[z]	56.0±7.7ab	82.0±6.9a	68.0±7.4ab	48.0±0.1b
	2 Years Posttrt. Mean±SEM percent survival			
1st	100.0± 0.0a	100.0± 0.0a	100.0± 0.0a	96.0± 4.0a
2nd	96.0± 4.0a	96.0± 4.0a	100.0± 0.0a	92.0± 4.8a
3rd	92.0± 4.8a	96.0± 4.0a	96.0± 4.0a	92.0± 4.8a
4th	96.0± 4.0a	84.0±11.6a	92.0± 8.0a	92.0± 4.8a
5th	92.0± 8.0a	76.0±14.7a	80.0±15.5a	88.0± 8.0a
PP	56.0±13.2a	56.0±16.0a	52.0±16.2a	52.0±18.5a

[x] Treatments C=control; Paclobutrazol rates X, 2X and 4X=40 ml, 80 ml and 160 ml per injection hole.
[y] Means within rows followed by the same letter are not significantly different (Student-Newman-Keuls test) (SAS Institute, 1985).
[z] PP=prepupal stage.
N=3 tree replicates.

Table 6. Influence of paclobutrazol treatments on the mean development and survival of *A. senatoria* in the field.

Mean ± SEM

	Total development (days)[v]				Percent survival			
T[w]	1989	N[x]	1990	N	1989	N	1990	N
C	32.6±0.6a[y]	3	35.8±0.3a	3	62.3±11.8a	3	57.8±12.1a	3
X	31.6±0.3a	3	35.2±0.5a	3	73.0± 4.0a	3	63.2±12.4a	3
2X	31.6±0.3a	3	34.7±0.9a	3	53.3± 6.1a	3	53.8±17.8a	3
4X	31.0±0.0a	3	34.2±0.7a	3	68.0±13.0a	2	43.3±14.0a	3
O[z]	31.7±0.2	12	35.0±0.3	12	63.8±4.3	12	54.0±7.0	12

[v] Development time from first instar to pupae.
[w] Treatments C=control; Paclobutrazol rates X, 2X and 4X=40 ml, 80 ml and 160 ml per injection hole.
[x] N=number of tree replicates.
[y] Means within columns followed by the same letter are not significantly different (Student-Newman-Keuls test) (SAS Institute, 1985).
[z] Overall mean.

Table 7. Influence of paclobutrazol treatments on the mean female pupal weight of *A. senatoria* in the laboratory and field.

	Mean±SEM female pupal weight (g)					
T[x]	1 yr lab posttrt	N[y]	1 yr field posttrt	N	2 yrs field posttrt	N
C	1.1±0.03b[z]	13	1.1±0.03b	32	0.7±0.09b	5
X	1.3±0.04a	20	1.3±0.02a	70	1.2±0.04a	8
2X	1.1±0.04b	16	1.3±0.02a	65	1.1±0.07a	7
4X	1.2±0.03ab	11	1.1±0.02b	46	1.2±0.06a	7

[x] Treatments C=control; Paclobutrazol rates X, 2X and 4X=40 ml, 80 ml and 160 ml per injection hole.
[y] N=number of pupae.
[z] Means within columns followed by the same letter are not significantly different (Student-Newman-Keuls test) (SAS Institute, 1985).

Chapter 4

Biological characteristics of orangestriped oakworm populations in southeastern Virginia

Introduction

Numerous reports on the biology of *Anisota senatoria* J. E. Smith (orangestriped oakworm) have been published (Lintner 1889, Lugger 1890, Felt 1905, Houser 1918, Felt 1926, Becker 1938, Beal 1952, Riotte & Peigler 1981, Drooz 1985, Johnson & Lyon 1988). *Anisota senatoria* populations in Connecticut were studied by Hitchcock (1958, 1961a,b,c); however, research has not been conducted on *A. senatoria* populations in Virginia. Data on the biology of *A. senatoria* may provide an explanation for damaging populations which have occurred during the last 8 years in southeastern VA (Coffelt & Schultz 1990b). Egg mass size, pupal mortality and number of generations varied between Connecticut (Hitchcock 1961b,c) and southeastern Virginia.

The objectives of this study were to examine several biological characteristics of *A. senatoria* populations in southeastern VA. These characteristics included egg mass size and development, pheromone attraction, blacklight trapping, adult emergence, laboratory larval development, pupal mortality, and comparison of first and second generation development, fecundity, and impact.

Materials and Methods

Egg development time and egg mass size. Eggs that were oviposited on *Quercus palustris* Muench., pin oak, and *Q. phellos* L., willow oak, in Norfolk, Virginia Beach, and

Chesapeake, VA were used in this study. Freshly oviposited eggs in 1987 and 1989 were examined daily and the number of days to eclosion were determined. The number of eggs per egg mass were counted from 1987-1990.

Pheromone attraction. Baited and unbaited traps were used in 1989 field experiments. Baited traps consisted of virgin females that were collected as they emerged from overwintering pupae. One virgin female was enclosed in a cylindrical (7 x 15 cm) wire cage suspended above a Pherocon A. M. sticky card (Trece Inc., Salinas, CA). A 5 ml water vial plugged with cotton was included in baited traps. Unbaited traps did not contain a female. Traps (45 baited and 45 unbaited traps) were placed in *Q. phellos* trees in a Norfolk, VA neighborhood, one trap per tree. Traps were 2 m above ground and at least 10 m apart, suspended in trees from June 30 - July 5, July 6 - 11, and July 12 - 17. The number of *A. senatoria* female and male moths captured per trap per day was recorded daily.

Blacklight traps. Three blacklight traps (as described by Gentry et al. 1967) were obtained from the USDA ARS Cotton Research Laboratory, Oxford, NC. Blacklight traps were suspended from *Q. phellos* branches, 2.5 m above the ground, from June 21- August 21, 1987-1988. Two traps were used in 1987 and one trap in 1988. Traps were placed in Norfolk, VA trees that had a history of *A. senatoria* infestation and were

examined daily. The number of female and male moths captured were recorded.

Adult emergence. A Norfolk, VA area that contained *Q. phellos* trees and had a history of large *A. senatoria* populations was selected for this study. Each morning from 8-11 am (EST) June 18-July 9, 1990, all female and male moths were counted as they emerged from overwintered pupae. Emergence of female and male moths were recorded daily (except July 8).

Laboratory development. In July, 1988, *A. senatoria* eggs were pinned on leaf undersides of 15 cm *Q. palustris* cuttings. Upon egg eclosion, five larvae were established per cutting. Cuttings were placed in 100 ml water-filled cups placed in 19 x 11 cm plastic boxes. Boxes were placed in an environmental chamber maintained at 26.6°C (L) and 21°C (D) and a photoperiod of 16:8 (L:D). Ten replicates were established. Larvae were examined daily and the date that 60% of the larvae molted to the next stage was recorded. Development time for each stage was determined.

Pupal mortality. Fifth instar *A. senatoria* were collected from Norfolk, VA in September of 1988 and 1989 as they crawled to the ground seeking suitable locations to pupate. Larvae were placed in 41 x 56 cm laboratory boxes with 3 cm of soil and allowed to pupate. Pupae were sexed

(Ehrlich et al. 1969) and separated into 16 wooden boxes (33 x 33 cm, 4 cm in depth) in 1988. Eight boxes received female pupae and eight boxes received male pupae, 25 pupae per box. Pupae contained in the boxes were covered with soil. Eight boxes (four with female and four with male pupae) were covered with a wooden lid that had a wire screen mesh. All 16 boxes were buried to a depth of 5 cm on September 21, 1988. In 1989, pupae were separated into four boxes. Two boxes received female pupae and two boxes received male pupae, 25 pupae per box. Two boxes (one with females and one with males) were covered, and all boxes were buried on October 12, 1989.

On June 27, 1989 eight boxes were unearthed and on June 27, 1990 two boxes were unearthed. Boxes were taken to the laboratory and the pupae were classified as viable, emerged, dead, or parasitized. Viable pupae were unbroken and showed movement when held. Emerged pupae had moved to the soil surface and eclosed at the dorsal tip. Dead pupae were broken and hollow. Parasitized pupae attacked by *Lespesia anisotae* (Webber) (Diptera: Tachinidae) were identified by either puparia or characteristic slits in *A. senatoria* pupae. Viable pupae were placed back in the boxes, covered with soil, and all boxes were left uncovered (no wooden lids) and reburied on June 27, 1989 and 1990. Screened cages were placed over the boxes to capture any emerging moths. Cages were checked daily

during July and the number and sex of moths recorded. On October 11, 1989, and November 8, 1990, all boxes were unearthed and pupae were classified into the previously described categories. Pupae were dissected to determine viable pupae.

1989 second generation population studies. Second generation *A. senatoria* larval populations were first observed on October 25, 1989, at the Hampton Roads Agricultural Experiment Station (HRAES), Virginia Beach, VA. The number of larvae and the number of infested trees were counted. Trees in Norfolk were examined for second generation larvae in October, 1989. Fifth instars were collected (681 larvae) on November 1, 1989, and placed in 41 x 56 cm plastic boxes filled with 3 cm of soil. Boxes were buried 5 cm in the ground and a screened cage was placed above the box to prevent larval escape. Larvae overwintered in the field boxes and on June 18, 1990, viable pupae were removed from the boxes, sexed and counted. Viable pupae were separated by sex into 18 x 14 cm plastic boxes with 3 cm of soil and buried under the canopy of a 1.5 m *Q. palustris* tree. A meshed 2.4 x 1.8 m tent was placed over the tree to capture emerging adults. Pupae were examined daily for adult emergence from June 19-August 10, 1990. On August 10, pupae were removed from boxes and classified as previously described. An additional category included moths that did not eclose. A sample of 45 pupae (23

female and 22 male) that contained all of the viable pupae were placed in laboratory containers. These pupae were dissected in September and categorized.

1990 second generation population studies. Fecundity of second generation moths was determined in 1990 from 126 *Quercus* located in the completely randomized design (CRD) plot (Chapter 8) at the HRAES. The number of egg masses and eggs per mass per *Quercus* species was counted in early October, 1990. The number of trees infested with second generation larvae in 1990 was also counted. Additional smaller plots of *Quercus* had been planted at the HRAES. There were 181 *Quercus* in these smaller plots and the number of infested trees were counted. Development time of *A. senatoria* was determined on six of the 11 *Quercus* species in the CRD plot. Larvae were examined daily and the date that 60% of the larvae molted to the next instar and the number alive at the end of each instar was recorded. Development time and survival in each instar were determined. Percent survival was based on the number of live larvae entering each stage.

Data were subjected to analysis of variance (ANOVA) and differences between three or more means were separated by Student-Newman-Keuls test (SAS Institute, 1985). Arcsin transformations were performed on percent survival data to maintain homogeneity of variance (Steel & Torrie 1980).

Results and Discussion

Egg development time and egg mass size. The mean number of days in the egg stage was 10.3±0.1 and ranged from 7.0-13.0 days, based on 123 egg masses. Differences in egg development time were nonsignificant ($P>0.05$) between 1987 and 1989 and between *Q. palustris* and *Q. phellos*. Egg development in this study was within the range of other reports. Lintner (1889) reported eggs eclosed in 7-10 days in New York. Hitchcock (1961a) observed in Connecticut that eggs took 12 days to eclose. Significantly more eggs per egg mass were found on *Q. palustris* compared to *Q. phellos* (Table 1). These *Quercus* species were frequently defoliated in southeastern VA. Egg masses on *Q. palustris* had a mean of 493.5±15.1 eggs per egg mass and ranged from 147-811. Egg mass size was large in this study, compared with some regions of the country. Hitchcock (1961b) did not report the host in Connecticut but found a mean of 127.2 eggs per egg mass and a range from 94-216. In another report, Hitchcock (1958) stated the number of eggs per egg mass ranged from 200-700. Lugger (1890) reported *A. senatoria* eggs per egg mass in Minnesota ranged from 350-675. Lintner (1889) reported an average egg mass size of 500 in New York. Hitchcock (1961b) suggested new *A. senatoria* infestations had more eggs per egg mass and declining populations had the least. Results from this study did not support that observation. Low or declining populations were

observed in 1987 and higher populations in 1989. However, differences in egg mass size were nonsignificant ($P>0.05$) between 1987-1990. This consistently large egg mass size contributed to large *A. senatoria* populations in southeastern VA.

Pheromone attraction. Significantly more males were captured in baited traps compared with unbaited traps (Table 2). A total of 692 males were captured with 98.7% in baited traps. No females were captured in traps. Significantly ($P<0.05$) more males were captured on baited traps July 6-11 (analysis not shown), which indicated peak activity. The mean longevity of females in traps was 3.7 ± 0.1 days (n=90 traps). These data demonstrated that virgin female *A. senatoria* moths produced a sex pheromone that attracted males. Solomon (1973) showed female *A. virginiensis* (Drury), pinkstriped oakworm, produced a sex pheromone and Riotte & Peigler (1981) reported *Anisota* species emitted pheromone and suggested pheromones may be chemically similar for all species. Identification and synthesis of the *A. senatoria* sex pheromone could provide for an effective monitoring tool.

Blacklight traps. The number of females, males, and total moths caught in blacklight traps were not significantly different ($P>0.05$) between years (1987, 1989), dates, and traps. Only 32 female and six male moths were trapped in 1987, and four females in 1988. Moths were not observed at

artificial lights during this four year study. One report stated *A. senatoria* moths were attracted to artificial lights (Johnson & Lyon 1988). Riotte & Peigler (1981) reported some *Anisota* species were attracted to lights but species with diurnal males were rarely trapped. Covell (1984) reported *A. senatoria* moths were diurnal and not easily collected. Peigler & Williams (1984) reported male *A. senatoria* moths seek females from approximately 1130-1530 h (EST). Blacklight traps should are not an accurate monitoring tool for *A. senatoria* populations. Pheromone traps or larval counts were more accurate. Riotte & Peigler (1981) reported *A. peigleri* (Riotte) larvae were abundant in northwestern South Carolina but adults were only occasionally attracted to lights because males were diurnal, a situation similar to that observed with *A. senatoria*.

Adult emergence. Daily emergence of female and male *A. senatoria* moths on 20 sample dates in 1990 showed peak emergence occurred on July 6 (Figure 1). The first moth was found on June 19, 1990, compared with June 23 and 26 in 1988 and 1989. Peak female emergence occurred on July 6 and peak male emergence occurred earlier, on July 2 (Figure 1), but large numbers of males also emerged on July 5. The mean number of moths that emerged per day from June 18-July 9 was 39.8$\pm$9.0 females and 18.0$\pm$4.3 males. A total of 796 moths were counted; 69% were females and 31% males. Since peak *A.*

senatoria adult emergence occurred the first week of July, egg monitoring should commence by the second week of July.

Laboratory development. Mean development ranged from 7.4±0.2 days for the first instar and 3.7±0.1 days for the prepupal stage (Table 3). *Anisota senatoria* had a mean life span of 33.5 days.

Pupal mortality. Pupael viability was determined on June 27, 1989 and 1990, after pupae overwintered for nine months (Table 4). Viable pupae that yielded adults were not significantly different ($P>0.05$) between treatments (covered or uncovered boxes), year, and sex. Only 1.2±0.6% (n=500 pupae) of the pupae produced adults in July, 1989 and 1990. Therefore, viable pupae that did not emerge in July, 1989 and 1990, attempted to overwinter for two years or attempted to emerge in September as second generation adults (Table 4).

Viable pupae and pupae that attempted to overwinter were not significantly different ($P>0.05$) between sex and year so data were pooled (Table 4). There was a significant treatment (covered or uncovered boxes) effect (Table 4). Half of the boxes were covered from fall, 1988 and 1989, to June, 1989 and 1990, to prevent predation by small mammals. Hitchcock (1961c) found mammalian predation on *A. senatoria* pupae was a significant source of mortality. A higher percentage of pupae was viable and attempted to overwinter in uncovered boxes compared with covered boxes (Table 4). Covered boxes may have

affected pupal survival because of increased soil temperatures and relative humidity in the boxes which provided a better environment for disease. Diseases may have contributed to mortality within boxes, although pupae were not examined for diseases in this study. Hitchcock (1961c) found a fungus and polyhedral virus killed 14.2% of *A. senatoria* pupae.

Pupae were unearthed in the fall of 1989 and 1990. Mortality attributed to natural factors, such as predation, diseases, weather, and *L. anisotae* parasitism was not significantly different ($P>0.05$) between treatments (covered and uncovered boxes) and sex. Covered boxes did not significantly reduce predation, probably because all covered boxes were uncovered from June to October and predation may have occurred. Parasitism rates were similar in covered and uncovered boxes because *L. anisotae* parasitized *A. senatoria* as larvae and emerged from pupae in the spring and early summer. The percentage of pupae that died from natural mortality factors was significantly higher in 1989, although parasitism rates were higher in 1988 (Table 4). All of the pupae that attempted to overwinter for two years or emerge as second generation adults were dead by the fall of 1990. Hitchcock (1961c) found 24.1 and 44.8% of *A. senatoria* pupae produced moths in 1959 and 1960, based on spring and fall counts of pupae in the soil. In this study, 0.7 and 3.0% of the pupae produced moths, which may be normal for *A. senatoria*

populations in southeastern VA. Comparisons between data collected by Hitchcock (1961c) and the present study were difficult because of differences in experimental technique, weather conditions, and geographical location.

Lugger (1890) reported that *A. senatoria* pupae remained in laboratory breeding cages for two years. Data in this study showed *A. senatoria* pupae were capable of overwintering for two years in the field, although all pupae were dead in two years. Of the many factors that may contribute to *A. senatoria* outbreaks, one factor may be small numbers of pupae emerging after successfully overwintering for two years.

1989 second generation population studies. Hitchcock (1958) reported one *A. senatoria* generation in Connecticut. Beal (1952) found one generation in North Carolina but suggested that two may occur. Covell (1984) reported that probably two generations of *A. senatoria* occurred in the southern United States from May to September. The presence of second generation *A. senatoria* from September to November, 1989 and 1990, was first reported in this study. Second generations were only found in populations located at the HRAES. Observations indicated that second generation larvae were not found in Norfolk, VA. Lower pesticide pressure at the HRAES compared with Norfolk, VA may have allowed a second generation to occur.

A total of 20 trees (*Quercus*) (9.2%) were infested by

second generation populations in 1989. Thirteen *Q. phellos*, three *Q. acutissima*, two *Q. palustris*, and one *Q. rubra borealis* and *Q. falcata* were infested. A higher percentage of first generation larvae pupated successfully compared with second generation larvae (Table 5). Second generation larvae formed pupae in mid to late November at which time higher mortality occurred because of colder weather.

When 1989 second generation pupae were buried on June 19, 1990, seven females (6.4%) and one male (1.0%) emerged from June 29-July 7, 1990. More adults may have emerged but heavy rain flooded the pupal boxes on July 11-12. By August 10, 1990, 54.5 and 71.0% of female and male pupae were dead, 16.4 and 19.4% were viable, and 22.7 and 8.6% had adults that did not eclose. A subsample of pupae revealed that only one female pupa was viable one year after pupation.

1990 second generation population studies. Second generation moths were first observed at the HRAES on August 28, 1990 and by August 30, 17 female and two males were found on grass blades. Two egg masses were observed being laid in mid-September, 1990. The egg stage was 17.0 days for both egg masses, longer than the 10.3 days for the first generation. Significantly ($P<0.05$) more egg masses were oviposited by second generation populations compared with first generation. A mean of 0.73 ± 0.1 and 0.3 ± 0.06 egg masses per tree were oviposited by second and first generation adults. The mean

number of eggs per egg mass was not significantly ($P>0.05$) different between generations.

There were significant ($P<0.05$) differences between *Quercus* species in the number of egg masses and eggs per mass (Table 6). These data suggest that *Q. coccinea*, *Q. bicolor*, *Q. falcata*, and *Q. acutissima* were the most preferred by 1990 second generation *A. senatoria* females. All four of these species held their leaves longer than the other species and green foliage was available until November. *Quercus coccinea* and *Q. acutissima* were among species most preferred by first generation *A. senatoria* populations and *Q. bicolor* and *Q. falcata* were intermediate in preference (Chapter 9). *Quercus alba* was the least preferred by both first (Chapter 9) and second generation populations.

Infested trees in the CRD plot (Chapter 9) and HRAES were compared from 1990 first and second generations (Table 7). Although eggs were oviposited on certain *Quercus* species, infestation may differ because larvae migrated to other species as trees were defoliated. These data showed *Q. coccinea* were more infested by second generation larvae and *Q. acutissima* and *Q. palustris* were more infested by first and second generation larvae. The 1990 second generation infested more trees than the first generation. Second generation larvae infested 32.5% of all trees available in the CRD plot while first generation infested 23.8%. There were 307 *Quercus*

trees available to second generation larvae at the HRAES and 26% were infested. The highest infestations of HRAES trees occurred on *Q. coccinea* and *Q. acutissima*. These data indicated that oviposition (Table 6) and infestation (Table 7) among *Quercus* species was similar. Second generation *A. senatoria* preferred *Q. coccinea*, *Q. bicolor* and *Q. acutissima*.

Field development of second generation populations was determined in 1990 and compared with first generation data (Chapter 9). Field development and percent survival were not significantly ($P>0.05$) different between *Quercus* species so data were pooled (Table 8). Mean development was longest for the first instar and shortest for the fifth instar. Field development was longer for the second generation compared with the first generation (Chapter 9). Field development from first to fifth instar was 43.3 days for the second generation (Table 8) compared with 34.5 days (Chapter 9) for first generation larvae. Observational data inidcated that colder temperatures from September to November and differences in foliage texture lengthened the developmental period for each instar. Additional factors include differences in plant nutrients, parasite and predator activity, and feeding efficieny. Feeny (1970) found high concentrations of water and nitrogen in spring oak foliage that sustained greater herbivore diversity than low nutrient and higher tannin concentrations in late season foliage.

In this study, several biological characteristics of *A. senatoria* populations in southeastern VA were described. Egg mass size was larger on *Q. palustris* compared with *Q. phellos*. Females produced a sex pheromone that attracted male moths. Blacklight traps were not effective for monitoring *A. senatoria* adults. Peak male emergence occurred on July 2, 4 days earlier than female. The mean life span was 33.5 days in the laboratory. Pupal mortality was high and only 1.2% of the pupae produced moths in 1989-1990. Pupae were capable of overwintering for two years in the field. A second generation occurred from September-November. Second generation *A. senatoria* oviposited more egg masses, infested more trees and had a longer development time compared with first generation. Large egg mass size, pupae that were capable of overwintering for two years and the presence of a second generation may partially explain the consistent *A. senatoria* populations that have occurred in southeastern VA.

Table 1. Mean number of *A. senatoria* eggs per egg mass on *Q. palustris* and *Q. phellos*, 1987-1990.

Quercus sp.	Mean±SEM No. Eggs per egg mass	N[y]	Range
Q. palustris	493.5±15.1 a[z]	79	147.0-811.0
Q. phellos	370.2± 9.0 b	135	112.0-616.0

[y]Number of egg masses sampled 1987-1990, Norfolk, Va.
[z]Means within columns followed by the same letter are not significantly (P<0.05) different (SAS Institute, 1985).

Table 2. Mean number of *A. senatoria* male moths captured at traps baited with virgin females, 1989.

Trap	Mean±SEM No. males captured June 30-July 5	N[y]	July 6-11	N	July 12-17	N
Baited	7.8±2.3 a[z]	14	24.6±6.0 a	18	10.1±3.7 a	13
Unbaited	0.1±0.1 b	14	0.3±0.2 b	18	0.1±0.1 b	13

[y]Number of traps.
[z]Means within columns followed by the same letter are not significantly ($P<0.05$) different (SAS Institute, 1985).

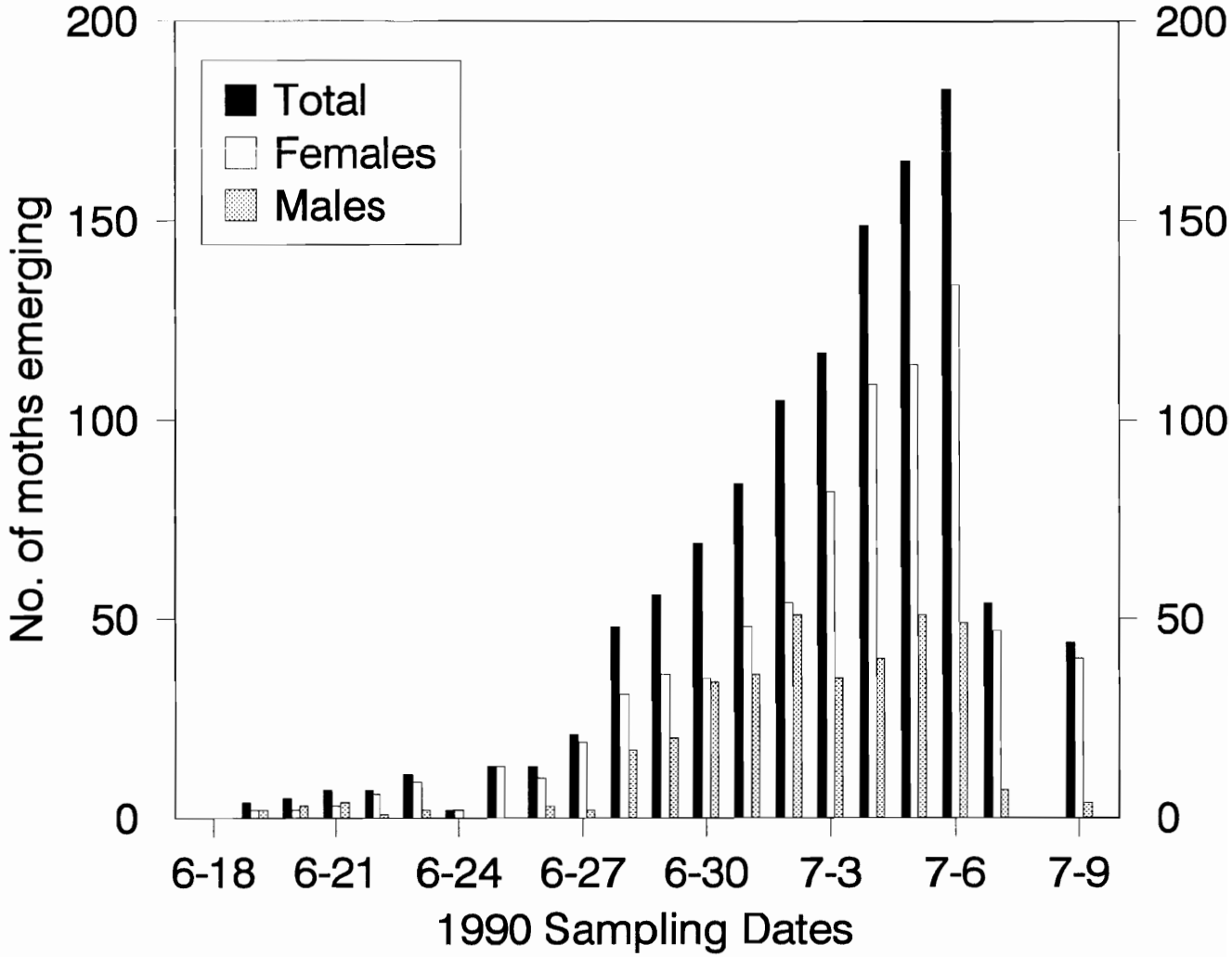

Figure 1. Daily emergence of female and male *A. senatoria* moths, 1990.

Table 3. Mean development of *A. senatoria* reared on *Q. palustris* in the laboratory, 1988.

Stage	Mean±SEM days in each stage	No. of replications
First	7.4±0.2	10
Second	6.3±0.1	10
Third	5.5±0.1	10
Fourth	5.2±0.1	10
Fifth	5.4±0.2	10
Prepupae	3.7±0.1	10

Table 4. Mortality factors of *A. senatoria* pupae, 1988-1989.

Treatment	Mean±SEM percent PV[x]		N[y]	OW		N
Uncovered	59.2±3.4	a[z]	5	58.4±3.7	b	5
Covered	39.2±5.0	b	5	36.0±4.1	a	5

Year buried	PD		N	PP		N
1988	79.5±3.0	b	16	19.7±2.8	a	16
1989	95.0±3.7	a	4	2.0±1.1	b	4

[x]PV=viable pupae on June 27, 1989 and 1990; OW=pupae that attempted to overwinter for two years or attempted to emerge as second generation adults; PD=dead pupae from natural mortality factors; PP=pupae parasitized by *Lespesia anisotae*.
[y]Number of boxes.
[z]Means within columns followed by the same letter are not significantly ($P<0.05$) different (*t* test, SAS Institute, 1985).

Table 5. Number of successful *A. senatoria* pupae in 1988 first and 1989 second generations.

Year	Generation	No. pupae and % of total that pupated successfully			
		Female		Male	
1988	First	493	36.0	215	15.7
1989	Second	110	16.2	97	14.2

Table 6. Mean number of 1990 second generation *A. senatoria* egg masses and eggs per mass from *Quercus* species.

Quercus sp.	Mean±SEM No. egg masses		N[y]	Mean±SEM No. eggs per mass		N
Q. falcata	1.9±0.9	a[z]	7	111.8±53.6	bc	7
Q. coccinea	1.7±0.3	ab	11	273.9±18.1	a	11
Q. bicolor	1.7±0.5	ab	14	164.0±35.2	b	14
Q. acutissima	1.5±0.4	abc	10	280.1±52.7	a	10
Q. palustris	0.8±0.5	abc	12	55.6±31.0	bc	12
Q. rubra borealis	0.3±0.1	bc	16	50.8±28.6	bc	16
Q. macrocarpa	0.3±0.2	bc	14	38.4±26.6	bc	14
Q. prinus	0.1±0.1	c	12	49.1±37.8	bc	12
Q. nigra	0.1±0.1	c	8	36.0±36.0	c	8
Q. phellos	0.0±0.0	c	9	0.0±0.0	c	9
Q. alba	0.0±0.0	c	13	0.0±0.0	c	13

[y]Number of tree replicates.
[z]Means within columns followed by the same letter are not significantly (P<0.05) different Student-Newman-Keuls test (SAS Institute, 1985).

Table 7. Percent of *Quercus* species infested with 1990 first and second generation *A. senatoria* populations.

Quercus sp.	Percent of trees infested: CRD plot first gen.	CRD plot second gen.	HRAES second gen.
Q. palustris	41.7	25.0	20.5
Q. bicolor	35.7	64.3	54.2
Q. acutissima	40.0	80.0	92.0
Q. rubra[z]	37.5	12.5	15.0
Q. falcata	28.6	42.8	50.0
Q. coccinea	18.2	100.0	100.0
Q. prinus	8.3	16.7	14.3
Q. macrocarpa	21.4	14.3	14.3
Q. phellos	22.2	0.0	10.7
Q. nigra	0.0	12.5	12.5
Q. alba	0.0	0.0	0.0
Total	23.8	32.5	26.0

[z]*Q. rubra borealis*.

Table 8. Mean development and survival of *A. senatoria* reared on *Quercus* for 1990 second generation larvae.

Instar	Mean±SEM Days in each instar	N[z]	Percent survival in each instar	N
First	11.6±0.5	15	67.7±5.4	16
Second	8.4±0.5	16	70.0±6.5	13
Third	7.9±0.5	12	53.0±8.8	12
Fourth	8.3±0.7	11	46.2±7.6	14
Fifth	7.1±0.4	8	54.2±5.4	11

[z]Number of tree replicates.

Chapter 5

Effect of group size on survivorship of orangestriped oakworm reared in the laboratory and field

Introduction

Behavioral adaptations by *Anisota senatoria* J. E. Smith (orangestriped oakworm) larvae strongly influence species survival. These adaptations include gregarious feeding and aposematic coloration. *Anisota senatoria* eggs are oviposited in a mass of 200-700 (Hitchcock 1958), and early (first-second) instars use large group size and gregarious feeding to enhance survival. Early green-yellow instars of *A. senatoria* skeletonize leaves and consume the entire leaf except for a network of veins (Hitchcock 1961a, Johnson & Lyons 1988). Enhanced survival by increased group size has been documented in Hymenoptera (Ghent 1960), Lepidoptera (Tsubaki 1981), and Coleoptera (Wade & Breden 1986). Advantages and disadvantages of group living have been examined (Stamp 1980). Advantages include feeding facilitation (Ghent 1960), decreased desiccation (Tsubaki 1981), thermoregulation (Seymour 1974), and lower predation (Tostowaryk 1972). Disadvantages of group living include feeding competition (Ito et al. 1982), cannibalism (Breden & Wade 1987), and predator and parasitoid attraction (Subinprasert & Svensson 1988).

Late (third-fifth) instars consume the entire leaf except for the main vein (Johnson & Lyons 1988) and are less dependent on large groups for survival. Late instar survival is enhanced by aposematic warning coloration. Aposematic coloration is evident in late instars with the development of

eight yellow-orange stripes on a black body (Riotte & Peigler 1981).

The objectives of this study were to determine the relationship between survivorship and group size in *A. senatoria* larvae reared in the laboratory and field and to examine mortality factors that may have contributed to lower survival.

Materials and Methods

Laboratory Studies. 1987 Experiments. Two-day-old first instars were transferred with a camel's-hair brush from eclosed egg masses to *Quercus palustris* Muench., pin oak, cuttings. Cuttings were placed in 100 ml water-filled cups and larvae were placed on cuttings enclosed in a 11 x 5 cm plastic cylinder covered with organdy cloth. Ten replications of 1, 3, 5, 7, 8, 9, 10, 11, 12, 15, 20 and 25 groups of larvae per cutting were placed in an environmental chamber maintained at 27°C (L) and 22°C (D) and a photoperiod of 16:8 (L:D). Cuttings were replaced as needed and larvae moved to fresh cuttings when cuttings dried. These groups were based on Hitchcock's (1961a) experiments where 8-10 larvae were considered the critical population at which significant mortality no longer occurred. Larvae were examined daily; the date of 60% larval molting to the next instar and the number of live larvae were recorded. Larvae were reared from first

instar to prepupae. Development time and survival for each stage were determined. Percent survival was based on the number of live larvae entering each stage.

1988-1989 Experiments. Mortality from placing larvae on leaves with a brush (1987 experiments) was eliminated in 1988-1989 experiments. *Anisota senatoria* eggs were removed from egg masses oviposited on *Q. palustris* leaves by cutting leaf sections containing a given number of eggs. Leaf sections were pinned on cuttings and a given number of larvae were allowed to develop. *Quercus palustris* cuttings were taken in July and placed in 100 ml water-filled cups. Cups were placed in 19 x 11 cm plastic boxes with two 3.2 cm ventilation holes that were covered with organdy cloth. Boxes were placed in the previously described environmental chamber and cuttings replaced as needed. Ten replications of the same groups as 1987 were used. Larvae were examined daily; the date of 60% larval molting to the next instar and the number of live larvae were recorded. Larvae were reared from first instar to prepupae for groups of one, three and five larvae only. Groups larger than five were reared for 10 days only because mortality was nonsignificant after 10 days. Development time and survival were determined as previously described. Larvae that pupated in 1989 laboratory studies were sexed (Ehrlich et al. 1969) and weighed from groups of one, three and five larvae.

Field Studies. 1987 Experiments. Two-day-old first instars were placed on leaves with a brush as previously described in 1987 laboratory experiments. Larvae were placed on leaf undersides of 1.8 m tall *Q. palustris* trees planted in 11.3 liter pots. Trees were arranged in a completely randomized design on an outdoor gravel bed that received daily overhead irrigation. Field experiments were conducted at the Hampton Roads Agricultural Experiment Station (HRAES), Virginia Beach, VA. Ten replications per group size were established. The same group sizes were used as previously described, except groups of 20 and 25 larvae were not included. Larvae were examined daily and the date of 60% larval molting to the next instar, number of live larvae, and mortality factors were recorded. Larvae were reared from first instar to the penultimate fifth instar. Development time, survival, and mortality for each stage were determined.

1988-1989 Experiments. Ten replications of the same groups as 1987 laboratory experiments were used and groups of 50 and 100 were included. Eggs were pinned on leaf undersides of *Q. palustris* planted in 11.3 liter pots. Larvae were examined daily and the date of 60% larval molting, number of live larvae, and mortality factors were recorded. In addition, seven replications of *A. senatoria* egg masses were included in 1990 and eclosion dates were recorded. Data recording was initiated 19 days after egg eclosion with groups

of larvae averaging 522 (average egg mass). Data recording was continued every 5 days until the penultimate fifth instar. Foliage was sufficient on each tree to allow for defoliation by each group and larvae were not handled or moved during the study.

Mortality was assessed in 1987-1989 according to four categories: environmental, predation, parasitism, and unknown factors. The first three categories were recorded only if signs of direct mortality were observed. Environmental factors included wind-blown effects, rain-wash and dead larvae in early morning dew. Predators were either observed consuming larvae or carrying them from leaves. Predatory signs included larvae caught in webs or impaled larval remains. Parasitized larvae were identified by discoloration and eventual parasite cocoons in the ventral abdominal region (Chapter 8). Percent predation and parasitism were determined by the ratio of the number of larvae eaten or parasitized by the number of hosts available for each group (Van Driesche 1983). Representative parasites and predators were sent to the USDA Systematic Entomology Laboratory in Beltsville, Md. and identified by the following: R. W. Carlson (Hymenoptera: Ichneumonidae), J. D. Coddington (Araneida: Clubionidae, Thomisidae, and Salticidae), O. S. Flint (Neuroptera: Chrysopidae), R. D. Gordon (Coleoptera: Coccinellidae), T. J. Henry (Hemiptera: Pentatomidae), and D. R. Smith (Hymenoptera:

Formicidae).

Data on 1987-1989 development and survival at each group size are presented by periods with Period 1 corresponding to days 1-7; Period 2, days 8-14; Period 3, days 15-19; Period 4, days 20-24; and Period 5, days 25-29. Each period corresponded to the prevailing *A. senatoria* instar present during that time. During Period 1, first instar were primarily present; Period 2, second instars; Period 3, third instars; Period 4, fourth instars; and Period 5, fifth instars. Periods 3-5 were 5 days in duration because *A. senatoria* larvae spend less time in the third, fourth, and fifth instars (Chapters 3 & 4).

1990 field experiments. The hypothesis that forced dispersal of first instar *A. senatoria* into smaller groups would cause decreased survival was tested in 1990 field experiments. Pesticide treatments were used to force dispersal. The same experimental design and *Q. palustris* trees as in 1987 field experiments was used in 1990. There were five replications of seven pesticide treatments. Pesticides were applied on July 24 to six-day-old groups of 366 larvae, one group per tree. Treatments were applied to runoff utilizing a CO_2 compressed air sprayer at 30 psi. Two rates per treatment of insecticidal soap (Ringer Corp., Minneapolis, MN)), 1% petroleum oil (Sun Refining & Marketing

Co., Marcus Hook, PA) and 1% neem seed extract (Grace Sierra Horticultural Products Co., Fogelsville, PA), derived from *Azadirachta indica* (A. Juss.) trees, were applied. Rates of insecticidal soap and petroleum oil were applied at 10 and 5 ml per liter. Neem seed extract was applied as a foliar spray at 6.3 and 3.2 ml per liter. A water treatment was applied to larval groups as a control. The number of live larvae and distance dispersed from larval groups in 24 and 48 hours were determined.

Statistical Analysis. Data were subjected to analysis of variance (ANOVA) (SAS Institute, 1985) and differences between treatment means were tested for significance ($P<0.05$) with Student-Newman-Keuls test (SAS Institute, 1985). Arcsin transformations were performed on percent survival data to maintain homogeneity of variance (Steel & Torrie 1980).

Results and Discussion

Laboratory Studies. Developmental periods were not significantly ($P>0.05$) different between all larval groups tested during three years of laboratory studies.

1987 Experiments. During Periods 1 and 5, groups of one and three larvae experienced 10.0 and 20.0% survival, figures that were significantly lower ($P<0.05$) than that of all other groups. Mean survival during Period 1 ranged from 10.0 to 84.0% and Period 5 ranged from 10.0 to 76.0% for groups of one and 11 larvae. The placement of larvae on cuttings with a

brush contributed to low survival. Many larvae died at the position in which they were placed.

1988-1989 Experiments. During Period 1 in 1988, mean survival was not significantly different between groups and ranged from 80.0 to 100.0% in groups of one and 20 larvae. During Day 10, significantly lower ($P<0.05$) survival occurred in groups of one larva compared with groups of five or more. Mean survival ranged from 60.0 to 100.0% in groups of one and 15 larvae. By Period 5, mean survival was not significantly ($P>0.05$) different between groups of one, three, and five larvae with means of 50.0, 80.0, and 82.0%, respectively. During Period 1 in 1989, mean survival was significantly lower ($P<0.05$) in groups of one larva compared with groups of 10, 12, and 20. Mean survival ranged from 60.0 to 99.0% in groups of one and 20 larvae. Mean survival was not significantly ($P>0.05$) different between all groups on Day 10. By Period 5, mean survival was not significantly ($P>0.05$) different between groups of one, three, and five larvae with means of 60.0, 80.1, and 70.0%, respectively. Mean male and female pupal weights were not significantly different between groups of one, three, and five larvae with a mean of 0.5 g (n=29 pupae) and 1.1 g (n=22 pupae), respectively.

Significantly lower ($P<0.05$) survival occurred during Period 5 in 1987 for groups of one and three larvae compared with 1988 and 1989. Lower survival can be attributed to a

different technique in 1987 compared with 1988 and 1989. Placing larvae on cuttings with a brush contributed to mortality and lower survival in 1987 and these results should be interpreted carefully. Hitchcock (1961a) suggested increased mortality occurred when small *A. senatoria* larvae were moved. Placing eggs on cuttings and allowing eggs to eclose in 1988 and 1989 did not contribute to mortality.

These laboratory experiments showed increased survival with increased group size. *Anisota senatoria* eggs are oviposited in large masses of 200-700 (Hitchcock 1958), and gregarious larvae are dependent on large groups for survival. Hitchcock (1961a) suggested a critical population level of 8-10 larvae per group as the point at which significant mortality no longer occurred in laboratory reared larvae. Hitchcock (1961a) did not indicate his method of establishing larval groups on leaves and his technique may have inflated the critical population level. In this study, mean survival was significantly lower in groups of one larva during Period 1 and Day 10 in 1988 and 1989 laboratory experiments. Mean survival was not significantly different between groups of five or more larvae. These data suggested a critical group size of only one to three larvae.

Field Studies. Developmental periods were not significantly ($P>0.05$) different between all larval groups tested during three years of field studies.

1987 experiments. Field survival in 1987 was lower than laboratory survival, with increased survival occurring as group size increased (Table 1). During Period 1, significantly lower survival occurred in groups of 1, 3, 5, and 7 larvae. During Periods 2-4, smaller groups had significantly lower survival than larger groups. By Period 5, groups of 1, 3, 5, and 7 larvae had significantly lower survival compared with groups of 12 and 15 larvae. Mean mortality was 64.8% and was highest during Period 1 and decreased the following weeks. In field experiments, the effects of placing larvae on leaves with a brush was not as critical as in the laboratory because mortality was high in small groups, even when eggs were placed on leaves in 1988 and 1989 field studies (Tables 2 & 3). Mean mortality in 1987 from environmental factors, predators, and parasites was 12.0, 1.7 and 2.8% and was not significantly ($P>0.05$) different between all groups during the five periods. During Period 1 in 1987, unknown mortality factors associated with groups of 1, 3, and 5 larvae were significantly higher ($P<0.05$) compared with groups of 12 and 15.

1988-1989 experiments. Field survival in 1988 and 1989 was lower than laboratory survival (Tables 2 & 3). Increased survival occurred with increased group size during Period 1 in 1988 (Table 2) and Periods 1-5 in 1989 (Table 3). During Period 1 in 1988 (Table 2), survival was not significantly

different between all groups except groups of one and nine larvae. This indicated that during Period 1 no larvae survived in groups of one larvae. By Period 2, survival was not significantly different between all groups. Mean survival was lower for groups of 1-15 larvae during Period 5 in 1988 (Table 2) compared with 1987 (Table 1), except for groups of 5 larvae. During Period 1 in 1989 (Table 3), significantly lower survival occurred in groups of 1, 3, 5, 7, 8, 9, 10, and 20 larvae compared with groups of 50 and 100 larvae. By Period 2, groups of 50 and 100 larvae had significantly higher survival than smaller groups (25 or less). Data for groups of 522 larvae were first taken during Period 3 and these groups showed significantly higher survival than for the remaining periods of the study. By Periods 4 and 5, significantly higher levels of survival also occurred in groups of 50 and 100 when compared with smaller groups. Mean mortality in 1988 and 1989 was 67.7 and 69.7%, respectively, and was highest during Period 1. These data suggested that a critical group size close to 50 larvae is necessary for higher survival. Data were not taken on survival between groups of 100 and 522 larvae, but survival differences are probably not significant but increase with increased group size.

Mean mortality differences from environmental factors, predators, and parasites in 1988 and 1989 were not significant ($P>0.05$) in comparison between all larval groups during the

five experimental periods. Mean mortality figures for these three factors were 10.7, 0.06, and 0.7% in 1988 and 0.03, 3.0, and 0% in 1989, respectively. During Period 1 in 1988, unknown mortality factors associated with groups of one larva were significantly higher ($P<0.05$) than groups of 25 larvae. During Period 1 in 1989, unknown mortality factors associated with groups of 1, 3, 5, and 7 larvae were significantly higher compared with groups of 50 and 100 larvae. Unknown mortality factors were not significantly different between groups for all other weeks in 1988 and 1989.

1990 field experiments. The existence of a critical group size (25-50 larvae) could have applications to integrated pest management (IPM) strategies. If groups of first instars could be forced to disperse into smaller groups the probability of larval survival would decrease. The biorational pesticide treatments of soaps, oils and neem did not affect larvae, did not cause dispersal from larval groups and mortality did not occur in 1990 field experiments. However, various feeding deterrents and repellents should be tested for their potential dispersing properties.

Inundative releases of egg parasites may result in smaller larval groups and additional mortality. Hitchcock (1961a) reported that *A. senatoria* egg parasitism by *Trichogramma* (Hymnenoptera: Trichogrammatidae) and *Tetrastichus* (Hymenoptera: Eulophidae) species approached 100%

in some Connecticut locations and suggested that remaining larvae would not survive because of this poor survival at small groups sizes. An inundative *Trichogramma minutum* release was conducted with varied results (Chapter 8); the release of additional egg parasites species should be considered.

Discussion. In laboratory and field experiments from 1987, 1988 and 1989, groups of one larva had significantly lower survival compared with other larval groups, especially during Periods 1 and 2. This can be explained by feeding behavior and silk production. Hitchcock (1961a) suggested that single larva had difficulty chewing on leaf margins but that grouped larvae fed freely once the leaf surface was broken. Riotte & Peigler (1981) surmised young *A. senatoria* larvae work as a team in cutting oak foliage. Therefore, *A. senatoria* larvae are probably unable to initiate feeding sites when reared singly. Nakamura (1977) developed a model for gregarious insects that predicted mortality in larval groups based on the probability that any one larva was capable of biting foliage within a limited time. The positive relationship between feeding facilitation and group size was documented for many insect species. *Halisidota caryae* (Harris) (Lepidoptera: Arctiidae) grew more rapidly and survived better in larger-sized groups than in smaller-sized groups, and Lawrence (1990) suggested feeding facilitation as

one explanation. *Neodiprion pratti* (Dyar) (Hymenoptera: Diprionidae) first instars fed more efficiently in groups of four than singly and had higher survival (Ghent 1960). Increased survival occurred in larger groups of *N. swainei* (Middleton) (Hymneoptera: Diprionidae) (Lyons 1962). Raupp (1982) found that *Plagiodera versicolora* (Laicharting) (Coleoptera: Chrysomelidae) larvae fed more successfully in groups of five or 10 than singly. *Pryeria sinica* (Moore) (Lepidoptera: Zygaenidae) larvae showed increased survival with larger group size (Tsubaki 1981). Small groups of larvae were unable to initiate feeding sites and poor performance resulted (Tsubaki 1981). Early instars of many gregarious insects feed in a coordinated fashion and feeding and foraging occurs in a phalanx, with the heads of individual insects in a row (Hood 1940, Breden & Wade 1987, Lawrence 1990). *Anisota senatoria* has been observed to feed in this manner (Coffelt, unpublished data). This behavior aids in feeding facilitation and initiation of feeding sites, but single *A. senatoria* larva can not feed in this manner, resulting in higher mortality.

Silk production is another factor that determines survival of single larva. A fine silken mat is produced by *A. senatoria* early instars (Hitchcock 1961a, Riotte & Peigler 1981) and permits larval groups to maintain their position on a leaf. Laboratory data in this study and observations by Hitchcock (1961a) suggests more than one larva is necessary to

produce the extensive silken mats required for survival. Hitchcock (1961a) reported young *A. senatoria* in small groups of one, two, and four larvae died when they fell from oak leaves and were unable to climb back on leaves, while few larvae in larger groups died in this manner. This was observed in the 1987, 1988 and 1989 laboratory studies for the small groups tested. When young larvae foraged beyond the silken mat, successful dispersal was dependent on silk production by the whole group (Hitchcock 1961a). Fifth instars were not observed to produce silk in any of the laboratory experiments.

Lower survival in small groups was also attributed to specific mortality factors. Mortality factors classified as unknown from 1987, 1988 and 1989 probably included parasite and predator activity. The parasite [*Hyposoter fugitivus* (Say) (Hymenoptera: Ichneumonidae] was recovered during all 3 years of field studies, and caused mean parasitism rates of 0-2.8%. Parasitism rates were low; however, Van Driesche (1983) stressed that parasitoid impact from such factors as host feeding by the parasitoid; paralyzed hosts where oviposition did not occur, host trauma, parasitoid oviposition, and behavior disruption contributed to higher host mortality in insects. *Anisota senatoria* larvae were undoubtedly exposed to these parasitoid factors, but they were not assessed for mortality.

Predators were probably the most significant mortality factor during 1987, 1988 and 1989 field experiments. Identified predators included three spider species: *Hentzia* species (Araneida: Salticidae), *Xysticus* species (Araneida: Thomsidae), and an unidentified clubionid species (Araneida: Clubionidae). Insect predators included larval and adult *Hippodamia* species (Coleoptera: Coccinellidae), worker *Monomorium minimum* (Buckley) (Hymenoptera: Formicidae), larval *Chrysopa rufilabris* (Burmeister) (Neuroptera: Chrysopidae), and nymphal and adult *Podisus maculiventris* (Say) (Hemiptera: Pentatomidae). The most abundant predators were spiders and *P. maculiventris*.

Anisota senatoria survivorship showed that significant mortality occurred during Period 1. Mean mortality was 64.7, 67.7, and 69.7% in 1987, 1988 and 1989 and significantly more unknown factors of mortality were associated with smaller groups of *A. senatoria* larvae than larger groups. Increased predation of *A. senatoria* larvae in smaller groups during Period 1 was a probable explanation. Many invertebrate predators were not observed on daily examination of larvae, but the unknown factors cause of mortality probably included significant predation. Lower predation in larger groups has been documented (Tostowaryk 1972), where pentatomid predators consumed fewer *N. swainei* and *N. pratti* larvae when presented with medium and larger groups than with smaller groups.

Lawrence (1990) found invertebrate predation, that included *P. maculiventris* and salticid spiders, accounted for at least a 10% daily decrease in *H. caryae* survivorship and greater than 50% total mortality. Higher mortality occurred during the first 6 days, particularly in small groups of 10 larvae. Lawrence (1990) did not find a significant difference between predator abundance and larval group size, but invertebrate predation, the most important mortality factor, decreased with increased group size. Feeny et al. (1985) found invertebrate predation was the major source of caterpillar mortality. Dempster (1967) found that a significant source of *Artogeia rapae* (L.) (Lepidoptera: Pieridae) larval mortality was nocturnal predation, a factor not measured in this study. Additionally, indirect effects of predators on gregarious caterpillars should be considered. Stamp & Bowers (1988) found that predatory wasps (*Polistes* species) killed *Hemileuca lucina* (Henry Edwards) (Lepidoptera: Saturniidae) caterpillars and indirectly affected larval fitness by slowing growth and forcing larvae into cooler microhabitats where leaves were of lower quality.

Lower *A. senatoria* mortality in later periods and instars was attributed to aposematic coloration and dispersal from groups. Third instar *A. senatoria* begin to develop aposematic coloration. Periods 3, 4, and 5 corresponded primarily to third, fourth, and fifth instars (Tables 1-3), where mean

mortality during the three year study was 3.7, 2.4 and 0.2%, respectively. Aposematism signals distastefulness, probably evolved in response to vertebrate predation (Matthews & Matthews 1978), and is effective against birds (Jarvi et al. 1981). Many aposematic insects have secondary defense mechanisms and *A. senatoria* larvae may have sequestered tannins that are present in high levels in late season oak leaves (Lawson et al. 1982, Riotte & Peigler 1981). Birds rarely attacked *A. larvae* late instars (Hitchcock 1958, Riotte & Peigler 1981).

Third instars began to disperse out of gregarious groups (Chapter 2) and fourth and fifth instars were found on individual leaves. This dispersal behavior coincided with development of aposematic coloration and decreased larval mortality. Wade & Breden (1986) found that the *P. versicolora* wandering phase coincided with increased survivorship. They suggested a diminished advantage of group living in older larvae because of increased competition between later instars within groups, and an increased risk of parasitism and cannibalism. In 1987, 1988 and 1989 *A. senatoria* field studies, the most likely reason that late instars had decreased mortality was that they dispersed to avoid competition between grouped larvae for limited oak foliage and developed aposematic coloration as a defense mechanism. Additional reasons were less susceptibility to environmental

factors.

The data collected during this study showed increased *A. senatoria* survival with increased group size. Laboratory studies showed a critical group size of one to three larvae. Higher survival occurred in the laboratory compared with the field that indicated environmental factors and predators and parasites were important sources of mortality. In field studies, a critical group size of between 25 and 50 larvae was determined. Lower survival in smaller groups was attributed to decreased feeding facilitation and silk production, parasitoid activity, and increased predation. Early (first-second) instars exhibited gregarious behavior and remained in large groups. Insecticidal soap, oil and neem treatments did not cause dispersal from gregarious groups or mortality. Later (fourth-fifth) instars dispersed from gregarious groups and developed aposematic coloration.

Table 1. Mean survival of *A. senatoria* at 10 group sizes, placed on foliage as larvae, under field conditions, 1987.

Group Size	Mean±SEM percent survival Period 1	2	3	4	5
1	0.0±0.0d[y]	0.0±0.0c	0.0±0.0d	0.0±0.0d	0.0±0.0d
3	9.9±7.0cd	3.3±3.3c	3.3±3.3cd	3.3±3.3cd	3.3±3.3cd
5	10.0±6.8cd	10.0±6.8c	8.0±6.1bc	6.0±6.0bcd	6.0±6.0cd
7	18.6±9.5cd	14.2±8.4bc	14.2±8.4abc	11.4±6.6bcd	11.4±6.6bcd
8	52.6±10.6ab	46.4±10.3ab	40.2±10.9a	40.2±10.9a	40.2±10.9a
9	56.8±9.7ab	46.7±10.8ab	34.5±7.3ab	29.9±6.6abc	39.5±3.9abc
10	45.0±12.4abc	42.0±11.0ab	36.0±9.7ab	33.0±8.6abc	33.0±8.6abc
11	40.0±7.9a-d	34.4±7.6abc	30.8±7.3abc	30.8±7.3abc	30.8±7.3abc
12	68.3±7.0a	55.7±5.7a	46.6±5.7a	45.0±5.5a	45.0±5.5a
15	51.2±9.4ab	46.0±10.1ab	37.9±8.8ab	35.2±8.6ab	35.2±8.6ab

[y] Means within columns followed by the same letter are not significantly diffferent (Student-Newman-Keuls test) (SAS Institute, 1985).
N=10 replications per group.

Table 2. Mean survival of *A. senatoria* at 12 group sizes, placed on foliage as eggs, under field conditions, 1988.

Group Size	Mean±SEM percent survival Period 1	2	3	4	5
1	0.0±0.0b[y]	0.0±0.0a	0.0±0.0a	0.0±0.0a	0.0±0.0a
3	10.0±10.0ab	0.0±0.0a	0.0±0.0a	0.0±0.0a	0.0±0.0a
5	48.0±14.9ab	14.0±9.4a	14.0±9.4a	6.0±6.0a	6.0±6.0a
7	34.4±11.7ab	5.8±3.8a	0.0±0.0a	0.0±0.0a	0.0±0.0a
8	26.4±12.8ab	13.8±10.2a	8.8±7.4a	1.3±1.3a	1.3±1.3a
9	62.3±11.4a	33.4±11.7a	15.6±9.2a	14.5±8.3a	13.4±8.4a
10	31.0±11.1ab	9.0±5.4a	0.0±0.0a	0.0±0.0a	0.0±0.0a
11	37.4±8.5ab	19.1±6.5a	11.7±4.8a	9.0±3.7a	9.0±3.7a
12	32.5±11.6ab	13.4±7.5a	10.0±6.8a	9.1±5.9a	9.1±5.9a
15	38.5±11.7ab	19.4±10.3a	14.7±8.2a	14.0±7.6a	14.0±7.6a
20	28.0±9.9bab	17.0±6.1a	12.0±4.4a	10.5±4.2a	10.5±4.2a
25	39.2±9.0ab	29.2±7.4a	21.6±5.6a	15.6±5.2a	15.6±5.2a

[y] Means within columns followed by the same letter are not significantly diffferent (Student-Newman-Keuls test) (SAS Institute, 1985).
N=10 replications per group.

Table 3. Mean survival of *A. senatoria* at 15 group sizes, placed on foliage as eggs, under field conditions, 1989.

Group Size	Mean±SEM percent survival Period 1	2	3	4	5
1	10.0±10.0c[y]	0.0±0.0b	0.0±0.0c	0.0±0.0c	0.0±0.0c
3	16.5±8.8c	0.0±0.0b	0.0±0.0c	0.0±0.0c	0.0±0.0c
5	10.0±10.0c	0.0±0.0b	0.0±0.0c	0.0±0.0c	0.0±0.0c
7	15.6±6.8c	0.0±0.0b	0.0±0.0c	0.0±0.0c	0.0±0.0c
8	20.1±9.5c	11.3±7.5b	11.3±7.5c	7.6±4.2c	7.6±4.2c
9	18.9±12.6c	0.0±0.0b	0.0±0.0c	0.0±0.0c	0.0±0.0c
10	6.0±4.9c	0.0±0.0b	0.0±0.0c	0.0±0.0c	0.0±0.0c
11	54.7±11.5abc	30.0±8.3b	19.0±6.2c	11.8±5.4c	9.1±5.6c
12	25.0±12.7bc	12.5±6.5b	4.1±3.3c	2.4±1.7c	1.6±1.6c
15	42.8±11.4bc	13.4±9.4b	7.4±6.6c	5.4±4.6c	4.7±3.9c
20	13.5±7.6c	7.0±4.7b	4.5±3.4c	3.0±3.0c	0.0±0.0c
25	35.6±13.1bc	25.6±11.5b	16.8±8.1c	15.6±7.6c	15.6±7.6c
50	83.6±4.0a	68.0±4.2a	57.4±4.1b	43.4±5.8b	41.4±4.9b
100	70.9±7.3ab	61.6±7.2a	49.0±6.8b	38.0±5.4b	37.7±5.4b
522	_____	_____	79.7±19.2a[z]	67.5±2.6a	67.5±2.6a

[y] Means within columns followed by the same letter are not significantly diffferent (Student-Newman-Keuls test) (SAS Institute, 1985).

[z] N=7 replications for a group size of 522; N=10 replications for all other groups.

Chapter 6

Impact of late season orangestriped oakworm defoliation on oak tree growth and vigor

Introduction

Late season defoliation during August and September, 1986-1990, by *Anisota senatoria* J. E. Smith, (orangestriped oakworm), was widespread in Norfolk, VA. (Coffelt & Schultz 1990b, 1991a). Although *A. senatoria* management strategies were established (Coffelt & Schultz 1990a), the effect of late season *A. senatoria* defoliation on tree physiology and growth was not determined. Hitchcock (1958) and Stimmel (1988) suggested *A. senatoria* late season defoliation was nonsignificant because *Quercus* (oak) trees are deciduous. Wargo (1981) found August artificial defoliation had less effect on tree vigor compared with April, May and June defoliation because trees did not refoliate.

Insect defoliation was correlated to growth reduction and tree mortality (Minott & Guild 1925, Church 1949, Heichel & Turner 1984, Miller & Wagner 1989, Wright et al. 1989). The amount of growth reduction and mortality was influenced by species, time of defoliation, tree vigor, soil moisture, and climatic conditions (Kramer & Kozlowski 1979). Insect defoliation reduced growth indirectly by decreasing photosynthesis and synthesis of growth regulators in the crown (Kramer & Kozlowski 1979). Kulman (1971) suggested growth reduction was proportional to foliage loss.

Carbohydrates are the most important constituents of woody plants comprising about 75% of their dry weight (Kramer

& Kozlowski 1979). Starches are the primary root storage carbohydrates in deciduous trees (Kramer & Kozlowski 1979, Loescher et al. 1990). Root starch reserves of deciduous trees has been used as an indicator of tree vigor (Carroll et al. 1983, Loescher at al. 1990). Starch reserves are sensitive to late season stress and decreased root starch affects tree performance the following year (Loescher at al. 1990). Defoliation decreased root starch reserves of several tree species (Staley 1965, Parker 1970, 1974, Parker & Houston 1971, Wargo et al. 1972, Herms et al. 1987). Dunn et al. (1987) showed winter starch reserves of *Quercus alba* L., (white oak), were an accurate predictor of susceptibility to *Agrilus bilineatus* (Weber) (Coleoptera: Buprestidae), twolined chestnut borer, attack.

Many of the studies that examined the relationship between defoliation and tree vigor have used artificial methods to simulate natural leaf loss. However, natural caterpillar defoliation does not remove leaf petioles, midribs, or blades (Kulman 1971) and occurs progressively over a 4 to 6 week period. Artificial defoliation is rapid, with leaf loss occurring in one day (Wargo 1981). Because of these differences, Wargo (1981) has emphasized the danger of applying artificial defoliation data to field studies.

The objective of this study was to determine the impact of late season defoliation by *A. senatoria* on *Quercus* growth

and vigor.

Materials and Methods

Fabric container study. *Quercus palustris* Muench., (pin oak), *Q. rubra borealis* (Michx. f.) Farw. (northern red oak), and *Q. phellos* L. (willow oak), were planted in 30.5 cm fabric containers (Root Control Inc., Oklahoma City, OK) on March 25, 1987. A randomized complete block design was used. There were five blocks and four trees of each species per block. Studies were conducted at the Hampton Roads Agricultural Experiment Station (HRAES), Virginia Beach, VA. Trees received 53 g of 18-6-12 Osmocote controlled release fertilizer (Grace Sierra Horticultural Products Co., Fogelsville, PA) in April of 1987 and 1988. Trees were also irrigated daily using a drip system. Treatments were 0, 1, 2, 3, and 4 years of natural defoliation. *Anisota senatoria* larvae were placed on trees in August of each year (1987-1990) in numbers sufficient to cause 100% defoliation. Trees that had 1 year of defoliation received the treatment in 1990. Larval migration to untreated trees was eliminated by placing a 15 cm band of tape, covered with petroleum jelly, on tree trunks. Tree height and caliper (thickness) were measured each year on June 13, 1988-1990. The difference in tree height between years was reported as top growth (Table 1). Trees were unearthed in October, 1990, severed at the base, and fresh weight (excluding roots) determined.

Roots that penetrated through the fabric containers were collected when trees were unearthed in October, 1990. Roots were washed, dried for 24 hours at 70°C, and weighed. One primary root per tree was debarked and ground with a Cyclotec mill (Model 1093, Tecator, Hoganas, Sweden) to yield 200 mg of tissue for analysis. Root starch analysis was conducted in the laboratory of Dr. Dale Wolf, Department of Crop and Soil Environmental Sciences, VPI & SU, Blacksburg, VA. Root starch was extracted by enzymatic hydrolysis, the preferred method because of its specificity (Haissig & Dickson 1979). Samples were solubilized in hot water to yield monosaccharides. Subsequent treatment with 0.02N hydrochloric acid yielded total free sugars (TFS) (monosaccharides and disaccharides). Total nonstructural carbohydrates (TNC) were enzymatically hydrolyzed with takadiastase enzyme (Miles Laboratory, Elkart, IN) (Haissig & Dickson 1979, Smith 1969). All solutions were assayed using an automated procedure (Davis 1976) and reported as glucose equivalents (dry matter) (Edmisten et al. 1988). Percent recovery was over 100% based on a glucose standard and corrections were not needed in the analysis (D. Wolf, pers. com.). Starch levels were determined (TNC - TFS) (Varn & Pfeiffer 1989) and presented as percentage dry weight.

Landscape *Quercus* study. *Quercus palustris* and *Q. phellos* were previously planted in the landscape at two

locations. Roots were sampled from *Q. palustris* that were located on city and private property in Norfolk, VA. Trees that were located between the sidewalk and street or between two sidewalks were planted in high stress sites with compacted, urban soil. Mean age was 45 years based on estimated planting date. Trees were consistent in diameter at breast height (dbh) (53.0±2.7 cm) and height (13.6±0.5 m), as indicated by the low standard error (mean±SEM). Natural populations of *A. senatoria* defoliated trees from mid-August to mid-September. Treatments were consecutive years of 100% defoliation from 1986-1990 (n=9 trees), partial defoliation from 1988-1990 (n=7), and no defoliation from 1986-1990 (n=7). Mean defoliation was 24.0±6.4% for 3 years in partially defoliated trees. Defoliation was assessed according to methods of Coffelt & Schultz (1990b).

Quercus phellos were previously planted at the HRAES and were 10 years in age when roots were first sampled. Trees were planted in a field that was a nonstress site with noncompacted soil. Trees were consistent in dbh (11.9±0.9 cm) and height (8.6±0.4 m), as indicated by the low standard error (mean±SEM). Treatments of 0, 1, 2, 3, and 4 years of natural 100% defoliation from 1987-1990 were used as previously described. Nine trees were untreated and the other treatments had three tree replicates. Untreated trees were protected with tape as previously described.

Roots from *Quercus palustris* and *Q. phellos* were sampled on nine dates over a 3 year period. Sample dates were December, 1988; March, May, September, 1989-1990; and January, December, 1990. Live roots were unearthed and sampled with a pruning lopper between 0.5-1 m from the trunk base. Roots 1 cm in diameter were cut into 10 cm long segments and placed in paper bags and dried for 24 hours at 70°C. Four roots per tree were collected from each cardinal direction in December, 1988, and March, May, and September, 1989. Two roots per tree were collected on the remaining dates. Percent starch and TNC were determined as previously described.

The effect of *Quercus* species, planting site and tree age were examined by comparing mean starch levels between trees. Mean starch levels were compared between *Q. palustris* and *Q. phellos*, between trees in stress and nonstress sites, and between trees 45 years and 10 years of age. Roots samples were taken in December, 1990.

Growth, starch, and TNC data were subjected to analysis of variance (ANOVA). Arcsin transformations were performed on percent data to maintain homogeneity of variance (Steel & Torrie 1980). Two means were separated by Student's *t* test and three or more means were separated by Student-Newman-Keuls test (SAS Institute 1985).

Results and Discussion

Fabric container study. *Quercus* fresh weight was not significantly different ($P>0.05$) between treatments, but there was a trend for decreased fresh weight with increased defoliation, especially among *Q. palustris* and *Q. phellos*. Undefoliated *Q. palustris* and *Q. phellos* had mean fresh weights of 7.9±2.9 and 14.2±2.3 kg compared with 1.9±0.3 and 9.7±0.7 kg for trees that received 4 years of 100% defoliation, respectively. Across all treatments, *Q. phellos* had significantly higher ($P<0.05$) fresh weight (9.9±0.9 kg) when compared with *Q. palustris* and *Q. rubra borealis*. *Quercus palustris* had significantly higher ($P<0.05$) fresh weight compared with *Q. rubra borealis* (4.7±0.9 and 0.8±0.2 kg).

Quercus palustris that received 3 and 4 years of defoliation had significantly less top growth (47%) when compared with trees that received 0 or 1 year of defoliation (Table 1). Differences in top growth were nonsignificant between treatments for *Q. rubra borealis*. *Quercus phellos* with 3 and 4 years of defoliation had significantly less top growth (36%) compared with undefoliated trees. Significant caliper reduction (58%) was found only in *Q. palustris* that had 2, 3, and 4 years of defoliation compared with 0 or 1 year of defoliation (Table 1).

Growth differed between *Quercus* species. Across all

treatments, *Q. phellos* had significantly more ($P<0.05$) top growth and caliper growth than either *Q. palustris* or *Q. rubra borealis*. *Quercus palustris* had significantly more top growth and caliper growth than *Q. rubra borealis*. The overall mean *Q. phellos*, *Q. palustris* and *Q. rubra borealis* top growth and caliper growth were 96.6±5.2 and 1.4±0.07 cm; 78.3±5.6 and 1.1±0.09 cm; and 33.9±4.2 and 0.4±0.05 cm, respectively.

Quercus palustris that received 4 years of defoliation was the only tree species that showed a significant reduction (89%) in root dry weight compared with undefoliated trees (Table 2). Mean starch was not significantly different among treatments for all *Quercus* species, but there was a trend for lower starch with increased defoliation in *Q. palustris*. Mean starch content was significantly higher ($P<0.05$) in *Q. palustris* (19.6±1.2%) compared with *Q. phellos* (15.1±1.2%) and *Q. rubra borealis* (14.0±1.3%). Total nonstructural carbohydrates (TNC) were not significantly different among treatments and followed a similar pattern as starch.

Top growth, caliper, and root weights were significantly reduced with increased defoliation in *Q. palustris* (Tables 1 & 2) that received 3 and 4 years of defoliation. *Quercus phellos* top growth was significantly reduced with 3 and 4 years of defoliation (Table 1). *Quercus palustris* and *Q. phellos* were primary *A. senatoria* hosts in southeastern VA. (Coffelt & Schultz 1990b). *Quercus rubra borealis* was

selected for this study because *A. senatoria* populations are present in the north central and northeastern United States, where *Q. rubra borealis* are common hosts (Lawson et al. 1982, Hitchcock 1961b). However, *Q. rubra borealis* grew poorly and was not adapted to the hot summer conditions of southeastern VA. Thirty percent mortality occurred the first year and the amount of growth was small (Tables 1 & 2).

This was the first study that used fabric containers to determine the influence of natural insect defoliation. This technique allowed for accurate removal of the root system and representative root samples for quantitative measurements. Chong et al. (1987, 1989) described the advantages and disadvantages of growing trees in fabric containers. One advantage was that significantly more starch was found in woody root tissue inside fabric containers. This increase in starch provided better survival when compared with conventionally grown trees. Mean starch in October, 1990, was higher in *Q. palustris* and *Q. phellos* grown in fabric containers (Table 2) compared with conventionally grown trees sampled in September, 1990 (Tables 3 & 4). However, differences in tree age and location existed, and *Q. palustris* and *Q. phellos* mortality was not observed.

Landscape *Quercus* study. Root TNC in *Q. palustris* and *Q. phellos* followed a similar pattern as starch, and these data are not presented. Starch has a seasonal cycle in many woody

plants (Kramer & Kozlowski 1979). Starch is the primary nonstructural storage carbohydrate in trees and its deposition begins throughout the tree after leaf expansion in the spring and peaks after shoot growth ceases in the autumn (Loescher et al. 1990). Because of seasonal changes in mobilization and usage, starch content is less stable during the spring and summer growing season than in autumn (Wargo 1981). Therefore, true defoliation effects are determined in the autumn because starch levels are normally high and stable in most deciduous species (Wargo 1981).

Mean root starch was not significantly different between compass directions ($P>0.05$); therefore, two roots were randomly selected per tree for samples in the 1990 dates. *Quercus palustris* that received 3, 4, and 5 years of consecutive 100% defoliation had significantly lower starch when compared with undefoliated trees on all sample dates (Table 3). *Quercus palustris* starch levels were high in September, 1989 and 1990 (Table 3). These levels corresponded with the autumn peaks in many deciduous trees (Kramer & Kozlowski 1979). *Quercus palustris* sampled in September after 4 and 5 years of defoliation had 79 and 49% lower starch levels when compared with undefoliated trees. *Quercus palustris* sampled in December after 3 and 5 years of defoliation had 56 and 79% lower starch levels when compared with undefoliated trees. Data from December, 1990, had a

sample size of four trees because two trees had died and one was in an advanced stage of decline (Table 3). Trees that averaged 24% defoliation from 1988-1990 did not show significant differences in mean starch content when compared with undefoliated trees on seven of nine sample dates.

A winter starch minimum occurs in many deciduous trees (Kramer & Kozlowski 1979). During the hardening process, starch is converted to sucrose at low temperatures (Siminovitch et al. 1953, Kramer & Kozlowski 1979, Worley 1979). January is the coldest month and starch levels decreased to 1.6±0.2% in the January 1990 sample. January samples were not taken in 1988 and 1991. Seasonal changes in starch differ between years depending on environmental conditions and species (Wargo 1981).

Data were not taken 1 and 2 years after defoliation (Table 3) and differences in starch levels between defoliated and undefoliated trees were probably not significant, based on research conducted by Wargo (1981). He investigated the influence of 100% artificial defoliation on 12-15 year old trees. Wargo (1981) found *Q. velutina* Lam., (black oak), and *Q. alba* starch levels were not significantly depleted 1 and 2 years after August defoliation. After 3 years of August defoliation, *Q. velutina* and *Q. alba* were significantly lower in starch when compared with undefoliated trees. During the fourth and fifth year, trees were not defoliated. Starch

levels during this period increased, but remained lower than levels in undefoliated trees.

Some studies have suggested that significant starch depletion occurred only after trees refoliated (Wargo et al. 1972). Natural July defoliation by *Heterocampa guttivitta* (Walker) (Lepidoptera: Notodontidae), saddled prominent, depleted starch in trees that refoliated the same year (Wargo et al. 1972). The amount of defoliation and refoliation was not given (Wargo et al. 1972). They concluded that significant starch depletion occurred only when defoliation was followed by immediate refoliation. However, these conclusions were contradictory for research where starch depletion occurred but refoliation amounts were small. Only 5-10% refoliation occurred in *Q. palustris* but significant starch depletion occurred (Table 3). August defoliation reduced starch, and refoliation was not reported (Wargo 1981). Loescher et al. (1990) found that late season defoliation had a significant impact on tree vigor and resulted in smaller carbohydrate reserves. Roots were more sensitive to stress compared with other tree organs (Loescher et al. 1990). Parker & Houston (1971) found that August defoliated *Acer saccharum* Marsh., (sugar maple), harvested in November had significantly lower food reserves when compared with undefoliated trees. Reserves consisted of proteins, lipids, and carbohydrates, including starch. Artificial defoliation

of *Carya illinoensis* Wang., (pecan), from August to November showed September defoliation caused the greatest starch depletion and affected growth the following spring (Worley 1979). Worley (1979) stated early defoliation of *C. illinoensis* followed by refoliation restored carbohydrate levels in above-ground tissues and large roots by winter. August artificial defoliation significantly depleted root starch reserves in *Prunus avium* L., (sweet cherry) (McCamant 1988).

Additional effects of late season defoliation may include delayed spring leaf flush, unlignified twigs, and susceptibility to winter damage (Kulman 1971). Houston & Kuntz (1964) found that after late season defoliation, *Acer* species buds swelled and were susceptible to winter damage from freezing and desiccation. July defoliation by *Popillia japonica* (Newman) (Coleoptera: Scarabaeidae), Japanese beetle, and severe drought in the autumn caused unlignified twigs and frost damage in *Ulmus americana* L., (American elm) (Wester 1943).

Quercus phellos that received 1 to 4 years of consecutive 100% defoliation did not show significant differences in mean starch content compared with undefoliated trees on any sample date (Table 4). High starch levels in September did not occur in 1989 but were present in 1990 (Table 4). The starch peak was delayed in 1989 and October or November samples may have

revealed an increase. Wargo (1981) reported that seasonal changes in starch differed between years, depending on environmental conditions.

In this study, factors that influenced starch content and vigor in *Quercus* were the species, planting site and tree age. Species vigor influenced the response to late season defoliation. *Quercus phellos* withstood late season defoliation better than *Q. palustris*, even after 4 years of defoliation (Tables 3 & 4). During this study, *Q. palustris* mortality from *A. senatoria* defoliation was observed, but similar mortality in *Q. phellos* was not observed. *Quercus palustris* grown in fabric containers had more root starch compared with *Q. phellos* (Table 2). On nonstress sites, *Q. palustris* 10 years in age had significantly more root starch when compared with similar aged *Q. phellos* (Table 5). However, more important factors such as growth, planting site and tree age influenced *Q. palustris* susceptibility to late season defoliation. Kramer & Kozlowski (1979) stated the impact of insect defoliation varied with plant species and angiosperms withstood defoliation better than gymnosperms. Within a genus, species varied in starch content and response to defoliation stress (Wargo 1981). Wargo (1981) found that when *Q. velutina* was artificially defoliated in August no significant differences in mean starch occurred when compared with undefoliated trees; however, in *Q. alba* significant

differences occurred. *Quercus phellos* in fabric containers produced more growth than *Q. palustris* (Table 1). *Quercus phellos* is a hardier tree and less susceptible to urban stresses compared with *Q. palustris* (Dirr 1983, Appel & Stipes 1984, 1986). *Quercus palustris* has been widely planted in the urban landscape (Dirr 1983), but has become less desirable because of physiological problems and diseases (Appel & Stipes 1986, Sinex 1991). Iron chlorosis in *Q. palustris* is a common condition (Sinex 1991). The pin oak blight fungus, *Endothia gyrosa* (Schw.) Fr., commonly colonizes urban *Q. palustris* in eastern VA (Appel & Stipes 1986). *Quercus palustris* grow well on wet sites with poorly drained soils; however, soils in urbanized regions of eastern VA have high sand content with a low capacity for soil moisture retention (Appel & Stipes 1984). Moreover, eastern VA is on the periphery of the natural range of *Q. palustris* and trees may be more susceptible to stresses because of unfavorable environmental conditions (Appel & Stipes 1984).

Planting site also influenced *Quercus* response to late season defoliation. *Quercus palustris* 45 years in age that was planted in high stress sites had significantly less starch compared with trees in nonstress sites (Table 5). The urban environment can be harsh on landscape plantings and stresses such as disturbed or compacted soil, road salt exposure, air pollution, and mechanical trunk injury are common (Potter

1986). In addition, reduction in plant vigor can occur from drought, poor soil aeration, freezing or extreme temperature fluctuations, defoliation, nutrient deficiency, chemical injury, and transplant shock (Harris 1983). Houston (1985) reported that growing conditions were unfavorable and that stress factors occurred frequently in urban sites.

Furthermore, tree age influenced *Quercus* response to late season defoliation. Defoliated *Q. palustris* 45 years in age had significantly less starch compared with undefoliated trees (Table 3) and the same results were found in trees 10 years of age (Table 5). Defoliated *Q. palustris* 45 years in age had significantly more starch compared with trees 10 years in age (Table 5). Mature defoliated trees may have stored more starch in the autumn to compensate for stress. However, differences in mean starch were nonsignificant between 45 year-old *Q. palustris* when compared with trees 10 years in age, when stress was not applied (Table 5). These data indicate that *Q. palustris* defoliation was an important factor regulating starch reserves.

Late season *A. senatoria* defoliation had a significant impact on *Quercus* growth and vigor. Data showed that *Q. palustris* and *Q. phellos* growth was significantly reduced with increased defoliation. Starch content and tree vigor in *Q. palustris* were significantly reduced by increased defoliation, and some tree mortality occurred. *Quercus phellos* was a

hardier species compared with *Q. palustris* and was not significantly affected by consecutive late season defoliations. In addition, data suggested that *Q. palustris* was affected more by *A. senatoria* late season defoliation when trees were planted in high stress urban sites. These data have important implications for *A. senatoria* management strategies. *Anisota senatoria* populations that cause 100% late season defoliation on *Q. palustris* should be monitored to prevent progressive decline in tree health.

Table 1. Mean top and caliper growth of *Quercus* species grown in fabric containers that were 100% defoliated by *A. senatoria*. Measurements were taken from June, 1988, to October, 1990.

	Quercus sp.[x]	Mean±SEM No. years of 100% defoliation 0	N[y]	1	N	2	N	3	N	4	N
Top	PO	93.7±11.9a	20	94.5±10.3a[z]	10	70.9± 7.2ab	15	63.2±13.7b	10	36.5± 8.2b	5
gr.	NR	35.7± 8.0a	15	38.2± 8.8a	9	41.3±11.2a	11	22.7± 6.2a	8	15.2± 4.3a	3
cm	WO	115.2± 9.3a	17	99.6±14.5ab	10	93.6±10.7abc	15	82.6± 7.3bc	10	65.0±10.5c	5
Cal	PO	1.6± 0.1a	20	1.4± 0.1a	10	0.8± 0.1b	15	0.5±0.09b	10	0.6± 0.1b	5
gr.	NR	0.5± 0.1a	15	0.4± 0.1a	9	0.3±0.09a	11	0.3± 0.1a	8	0.4± 0.1a	3
cm	WO	1.6± 0.1a	17	1.6± 0.1a	10	1.0± 0.1a	15	1.3± 0.1a	10	1.4± 0.1a	5

[x] *Quercus* species: PO=*Q. palustris* (pin oak), NR=*Q. rubra borealis* (northern red oak), WO=*Q. phellos* (willow oak).
[y] N=number of trees.
[z] Means within rows followed by the same letter are not significantly different (P>0.05) Student-Newman-Keuls test (SAS Institute, 1985).

Table 2. Mean dry weight and starch of *Quercus* species grown in fabric containers that were 100% defoliated by *A. senatoria*, 1987-1990.

	Quercus sp.[w]	Mean±SEM No. years of 100% defoliation 0	N[x]	2	N	3	N	4	N
Total[y]	PO	1.9± 0.7a[z]	5	1.0±0.2ab	5	0.6± 0.1ab	5	0.2±0.03b	5
root	NR	0.2±0.09a	3	0.4±0.1a	3	0.1±0.03a	5	0.2± 0.1a	3
weight	WO	2.0± 0.4a	4	1.3±0.4a	5	1.2± 0.3a	5	0.8± 0.1a	5
Percent	PO	21.1± 1.1a	5	20.1±1.1a	5	19.7± 4.5a	5	17.1± 2.2a	5
starch	NR	14.4± 4.8a	3	11.6±0.7a	3	14.2± 1.0a	5	15.5± 4.6a	3
content	WO	17.7± 1.6a	4	12.2±0.9a	4	14.4± 1.7a	5	16.2± 3.8a	5

[w] *Quercus* species: PO=*Q. palustris* (pin oak), NR=*Q. rubra borealis* (northern red oak), WO=*Q. phellos* (willow oak).
[x] N=number of trees.
[y] Dry weight (kg) of roots in fabric containers.
[z] Means within rows followed by the same letter are not significantly different (P>0.05) Student-Newman-Keuls test (SAS Institute, 1985).

Table 3. Mean starch content in roots of *Q. palustris* that were 24 and 100% defoliated by *A. senatoria*, 1986-1990.

Sample Dates	Mean±SEM percent starch Undefol.	N[y]	Mean of 24% defol.	N	No. years of 100% defoliation 3	N	4	N	5	N
Dec. 1989	6.6±0.8a[z]	7	4.8±1.0ab	7	2.9±0.8b	7				
Mar 1989	5.0±0.8a	7	1.9±0.5b	7	1.7±0.3b	7				
May 1989	3.9±0.5a	7	3.5±0.3a	7	2.5±0.2b	8				
Sep. 1989	9.4±1.8a	7	6.5±1.3a	7			1.9±0.8b	8		
Jan. 1990	1.6±0.2a	7	1.6±0.2a	7			0.9±0.1b	9		
Mar. 1990	2.6±0.5a	7	1.8±0.3ab	7			1.2±0.2b	9		
May 1990	3.6±0.9a	7	1.2±0.3b	7			1.1±0.2b	9		
Sep. 1990	13.7±1.9a	7	13.0±1.4a	7					7.0±1.3b	5
Dec. 1990	17.0±1.5a	7	12.9±2.2a	7					3.5±1.3b	4

[y] N=number of trees.

[z] Means within rows followed by the same letter are not significantly different (P>0.05) Student-Newman-Keuls test (SAS Institute, 1985).

Table 4. Mean starch content in roots of *Q. phellos* that were 100% defoliated by *A. senatoria*, 1987-1990.

Sample Dates	Mean±SEM percent starch No. years of 100% defoliation							
	Undefol.	N[y]	1	N	2	N	3	N	4	N
Dec. 1989	12.2± 2.4[z]	9			11.9±0.5	3				
Mar 1989	2.9± 0.1	9			2.5±0.2	3				
May 1989	0.9±0.09	9			1.4±0.4	3				
Sep. 1989	0.5±0.03	6	0.3±0.08	3			0.4±0.08	3		
Jan. 1990	1.9± 0.8	6	0.6± 0.1	3			1.3± 0.3	3		
Mar. 1990	1.7± 0.3	6	1.8± 0.3	3			2.8± 2.0	3		
May 1990	0.7± 0.2	6	0.4± 0.2	3			2.0± 1.0	3		
Sep. 1990	10.5± 1.7	6			5.3±0.8	3			4.5±1.3	3
Dec. 1990	13.6± 0.6	6			7.0±3.9	3			6.3±4.2	3

[y] N=number of trees.

[z] Means were nonsignificant between treatments in rows for two means (*t* test, P>0.05) and three means for all sample dates (P>0.05) (Student-Newman-Keuls test) (SAS Institute).

Table 5. Comparison of mean starch between species, planting site and age of *Quercus*, December, 1990.

Comparisons[w]	Stress[x]	Mean±SEM percent starch N[y]			N	P[z]	Sign. value	*t*
NS,PO,Y vs NS,WO,Y	N	18.9±1.4	4	-	13.6±0.6	6	<0.001	3.79
S,PO,O vs NS,PO,O	S	12.2±1.7	10	-	16.6±3.5	9	<0.100	-2.04
S,PO,Y vs NS,PO,Y	D	3.4±1.0	4	-	18.9±1.4	4	<0.001	-8.50
S,PO,O vs S,PO,Y	D	14.1±4.3	3	-	3.4±1.0	4	<0.050	2.76
NS,PO,O vs NS,PO,Y	N	16.6±3.5	9	-	18.9±1.4	4	>0.100	-1.77

[w] S=stressed, NS=nonstressed; PO=*Q. palustris* (pin oak), WO=*Q. phellos* (willow oak); O=45 years, Y=10 years.
[x] Stress factors: N=no stress, S=urban sites, D=defoliation.
[y] N=number of trees.
[z] Levels of probability between comparisons and associated *t* value (*t* test) (SAS Institute, 1985).

Chapter 7

Relationship between orangestriped oakworm frass and instar, host plant, and defoliation

Introduction

Anisota senatoria J. E. Smith (orangestriped oakworm) has caused significant defoliation of *Quercus* species planted in the urban landscape (Coffelt & Schultz 1990a,b). A citizen survey (Chapter 11) indicated *A. senatoria* frass was a serious problem. Frass was observed by 84% of the citizens and 61% thought frass and crawling larvae were more significant than defoliation (Coffelt & Schultz 1991c). Lepidopterous larvae produce large fecal pellets that fall to the ground beneath the host plant. Pellet counts can give estimates of larval populations (Koehler 1987). Estimating larval densities of forest defoliators has been documented (Green & DeFreitas 1955, Liebhold & Elkinton 1988a,b). Volney et al. (1983) studied the relationship between lepidopteran frass and larval activity. They found collecting lepidopteran frass on sticky cards was an accurate sampling method that estimated larval populations and facilitated control decisions. Furthermore, frass size can be used to estimate instar distribution (Bean 1959, Liebhold & Elkinton 1988a).

The objectives of this study were to examine the relationship between *A. senatoria* frass and instar, host plant, and defoliation.

Materials and Methods

1989 field experiments. Fifteen *Quercus palustris* Muench. (pin oak) were planted in November, 1988, at the

Hampton Roads Agricultural Experiment Station (HRAES), Virginia Beach, VA and were used in 1989 field experiments. *Anisota senatoria* egg masses were collected from Norfolk, VA and pinned to leaf undersides on July 25, one egg mass per tree. Egg masses were equivalent in size and averaged 493 eggs (Chapter 3). Egg masses were examined daily and eclosion date recorded. A circular piece of polypropylene landscape fabric (DeWitt Co. Inc., Sikeston, MO) was placed beneath the canopy of each tree to collect fallen frass. The soil beneath the fabric was leveled and a slight inward slope was constructed to facilitate frass collection. Each landscape fabric section measured 2.62 m^2. When 60% of the larvae per tree had molted to the next instar, frass was swept into paper bags and air-dried (Bean 1959).

Subsamples of 25 pellets from each tree and instar were taken and each pellet length was measured to the nearest 0.01 mm using an ocular micrometer (Bean 1959, Volney et al. 1983, Liebhold & Elkinton 1988a). *Anisota senatoria* frass was separated from other debris in the bags and weighed to the nearest 0.01 g.

1990 laboratory experiments. *Anisota senatoria* eggs were pinned on leaf undersides of 11 *Quercus* species cuttings. Upon egg eclosion, larvae were removed with a probe to establish five per cutting. Cuttings were taken from *Quercus*

planted in 1985 at the HRAES. Cuttings were placed in 100 ml water-filled cups that were positioned in 19 x 11 cm plastic boxes. Boxes were placed in an environmental chamber maintained at 26.4°C (L) and 21°C (D) and a photoperiod of 16:8 (L:D). Five replications per host plant were established. *Quercus* cuttings used were: *Q. acutissima* Carruth. (sawtooth oak), *Q. alba* L. (white oak), *Q. bicolor* Willd. (swamp white oak), *Q. coccinea* Muenchh. (scarlet oak), *Q. falcata* Michx. (southern red oak), *Q. macrocarpa* Michx. (bur oak), *Q. nigra* L. (water oak), *Q. palustris* (pin oak), *Q. phellos* L. (willow oak), *Q. prinus* L. (chestnut oak), and *Q. rubra borealis* (Michx.f.) Farw. (northern red oak).

When 60% of the larvae had molted to the next instar, frass was collected from the boxes and air-dried. Frass length and weight were measured as previously described. Total frass weight per host plant was calculated. Late instars (fourth and fifth) were used to calculate frass weight per larva. Frass per larva per host was calculated by dividing the total weight by the number of late instars alive at experiment conclusion.

1990 field experiments. Eighteen *Q. palustris*, planted at the HRAES, were used in 1990 field experiments. *Quercus palustris* were measured to obtain mean diameter and height. Because trees were only 2 years in age, diameter at 30 cm

above the ground was measured for each tree. Eggs from egg masses were removed with a probe to establish 194 viable eggs per mass. Egg masses were pinned to leaf undersides. Eggs eclosed on July 21 and 26, and the number of live larvae were recorded per tree on August 4, 15, and 18. The same landscape fabrics were used on the ground to collect frass in 1989-1990. Percent defoliation was assessed (Coffelt & Schultz 1990b) on August 31 after all larval feeding had ceased. Frass from larvae that fed from late July to late August was collected on August 31 and weighed. Frass that fell outside the perimeter of the fabric was collected with a brush along the entire periphery of the fabric, placed in paper bags, and weighed.

Data from 1989 field and 1990 laboratory experiments were subjected to analysis of variance (ANOVA) and means separated by Student-Newman-Keuls test (SAS Institute 1985). Field data in 1990 were analyzed by simple linear regression (SAS Institute 1985).

Results and Discussion

1989 field experiments. Frass length was an accurate indicator of *A. senatoria* instars (Table 1). Frass from first instars had a mean length of 0.58±0.03 mm and frass from fifth instars had a mean of 3.33±0.09 mm. Frass measurements may vary with factors that affect size of individuals, such as host plant, host quality, and population density (Lance et al. 1986, Liebhold & Elkinton 1988a). Sampling frass predicted

instars when *A. senatoria* were reared on *Q. palustris*, grown in VA environmental conditions, and initial population densities were 194 larvae. Frass weight indicated fifth instars produced the most frass (Table 1), about 92% of the total frass was produced by the last two instars. All trees experienced 100% defoliation.

1990 laboratory experiments. Host plants significantly affected *A. senatoria* frass length and weight of frass produced per larva (Table 2). Frass length was significantly longer in first instars when larvae were reared on *Q. nigra* compared with ten of the remaining species; in second and fourth instars when larvae were reared on *Q. nigra*, *Q. phellos*, *Q. coccinea* and *Q. palustris* compared with six species; and in fifth instars when larvae were reared on *Q. nigra* and *Q. coccinea* compared with six species. Frass length was significantly shorter in second instars when larvae were reared on *Q. alba* compared with 6 other species, in fourth instars compared with eight species, and in fifth instars compared with five species. There was a trend for higher frass weight per larva when reared on *Q. nigra*, *Q. phellos*, *Q. rubra borealis*, *Q. coccinea* and *Q. palustris*. *Quercus palustris* and *Q. phellos* are heavily defoliated by *A. senatoria* in southeastern VA (Coffelt & Schultz 1990b), and *Q. nigra* are commonly attacked. *Quercus coccinea* is not common in southeastern VA but is closely related to *Q. palustris*

(Dirr 1983). These data suggested a difference in host plant preference by *A. senatoria* larvae. Leaf quality of the different host plants probably influenced larval feeding and consequent frass production. Larval host plants should be considered when sampling frass to determine instar. Volney et al. (1983) found leaf quality affected lepidopteran frass production.

1990 field experiments. The mean number of larvae in 1990 that survived to the fifth instar was 113 or 58% of the initial population. Similar survival to the fifth instar was found in 1989 gregarious behavior experiments (Chapter 5). The mean weight of frass per larva in 1990 field experiments was lower than that observed in 1990 laboratory experiments (0.9 and 2.3 g, respectively). More rapid and enhanced larval development occurred in the laboratory compared with the field (Chapters 4 & 9) and larger frass was deposited. Volney et al. (1983) stated that experiments that are designed to correlate frass weight with defoliation are needed in the urban landscape. Field experiments conducted in 1990 determined this relationship. There was a significant ($P<0.0001$) linear relationship between the weight of *A. senatoria* frass and percent defoliation (Figure 1). The coefficient of determination was high ($r^2=0.62$) and indicated 62% of the variation in (y) defoliation can be explained by

(x) frass weight. Based on the weight of *A. senatoria* frass collected on a 2.62 m^2 landscape fabric, defoliation of *Q. palustris* can be predicted.

Field experiments in 1990 used small *Q. palustris* of mean diameter 6.3±0.2 cm and mean height of 2.1±0.05 m (Figure 1). Small *Q. palustris* are frequently attacked in the urban landscape and these data have widespread application in urban forestry. Data could be extrapolated to include larger *Q. palustris* but may not apply to different *Quercus* species.

The circular landscape fabric used in this study provided a reliable and efficient method to collect *A. senatoria* frass. The amount of frass that fell outside the perimeter of the 2.62 m^2 fabric in 1990 averaged 10.0±4.0% (n=18 trees) and the fabric collected 90.0% of all frass that was deposited. Fabrics have been used for erosion control, soil separation, drainage installation, and landscape weed control (Derr & Appleton 1989). The landscape fabrics used in this study were durable over the two month sampling period and prevented weed growth. Landscape fabrics are porous and allow for exchange of water and air. During the few periods that rainfall occurred, water soaked through the fabric and frass remained on the fabric surface. The size and shape of *A. senatoria* frass appeared to be unaffected by rainfall. Bean (1959) found rainfall did not significantly alter *Choristoneura*

fumiferana (Clemens), spruce budworm, frass pellet size and shape.

Frass has been sampled with circular cone-shaped traps (Bean 1959) and sticky cards placed in petri dishes attached to metal rods (Volney et al. 1983). Liebhold & Elkinton (1988a) tested five trap designs for collecting gypsy moth frass and found a funnel trap was the most reliable and efficient. Although a comparison between funnel traps and fabrics was not conducted in this study, fabrics probably were an easier method to collect frass. The landscape fabric used in this study was an efficient method to collect frass and may have applications in other landscape entomology research. Fabrics are inexpensive, commercially available, and easy to install in an urban landscape.

These data showed that *A. senatoria* frass could be used to differentiate larval instars. However, frass length and weight varied with host plant. Landscape fabrics recovered 90% of all frass deposited and were a reliable sampling method. The weight of *A. senatoria* frass per 2.62 m^2 landscape fabric predicted defoliation of small sized *Q. palustris*. This information has practical value and could provide for a decision-making guideline for *A. senatoria* control.

Table 1. Mean length and weight of *A. senatoria* frass, 1989 field experiments.

Instar	Mean±SEM Length (mm)	N[x]	Mean±SEM Weight (g)	N
First	0.58±0.003e[y]	15	4.96±0.33c	15
Second	1.06±0.01 d	9	12.63±1.76c	15
Third	1.64±0.02 c	11	35.54±3.89c	15
Fourth	2.57±0.05 b	11	233.65±17.5b	11
Fifth	3.33±0.09 a	6	340.33±70.8a	6

[x] Number of *Q. palustris* (pin oak) sampled.
[y] Means within columns followed by the same letter are not significantly different (P>0.05) (Student-Newman-Keuls test) (SAS Institute, 1985).

Table 2. Influence of *Quercus* species on mean length of *A. senatoria* frass and frass per larva, 1990 laboratory experiments.

Quercus sp.	Mean±SEM pellet length (mm) Instars First	Second	Third	Fourth	Fifth	Frass wt. per larva (g)
nigra	0.55±0.02a[x]	0.79±0.01ab	1.21±0.02[y]	2.62±0.06a	3.41±0.10a	3.45
phellos	0.53±0.01ab	0.82±0.04ab	1.23±0.01	2.50±0.02ab	3.26±0.10ab	3.08
coccinea	0.49±0.01bc	0.85±0.01a	1.26±0.03	2.44±0.05b	3.41±0.05a	2.46
falcata	0.48±0.01bc	0.77±0.01b	1.35±0.01	2.55±0.04ab	3.12±0.11a-d	2.29
macrocarpa	0.48±0.01bc	0.70±0.02cd	1.13±0.008	2.07±0.03de	2.89±0.03cde	1.66
prinus	0.47±0.01c	0.70±0.01cd	1.16±0.04	2.24±0.01c	2.84±0.06de	2.07
bicolor	0.46±0.01c	0.68±0.01cd	1.09±0.01	2.25±0.04c	2.96±0.07b-e	1.76
palustris	0.46±0.01c	0.81±0.02ab	1.27±0.03	2.43±0.06b	3.16±0.10abc	2.36
acutissima	0.45±0.02c	0.68±0.01cd	1.15±0.05	2.06±0.01de	2.71±0.05e	1.73
rubra[z]	0.44±0.01c	0.75±0.01bc	1.12±0.02	2.14±0.03cd	2.98±0.01b-e	2.65
alba	0.43±0.007c	0.64±0.005d	1.04±0.02	1.04±0.02e	1.94±0.01e	2.30

[x] Means within columns followed by the same letter are not significantly different (P>0.05) (Student-Newman-Keuls test) (SAS Institute, 1985).
[y] Means are not significantly different (SNK).
[z] *Q. rubra borealis*.
N=Five replications per instar and host.

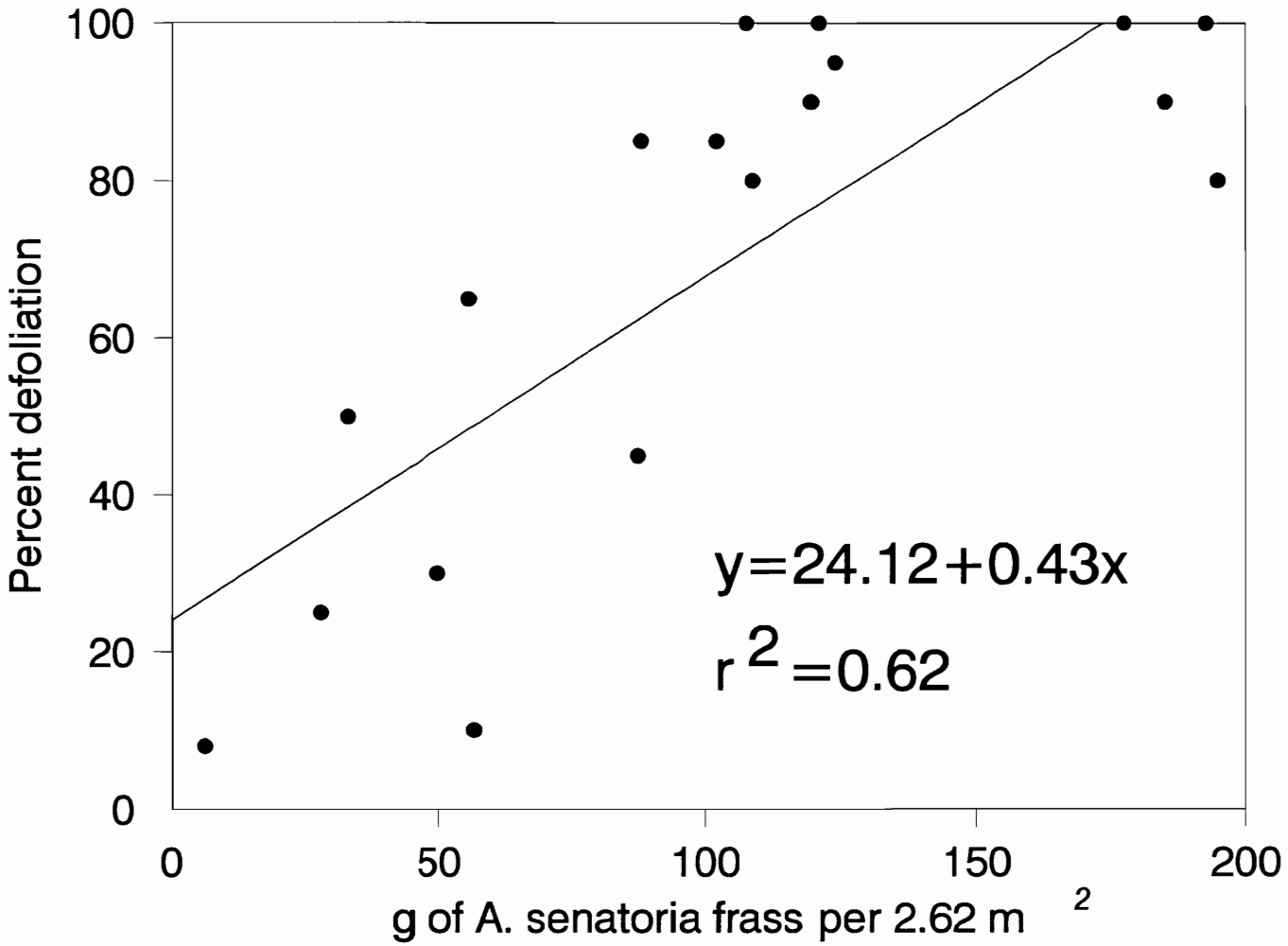

Figure 1. Regression equation for the relationship between the total amount of *A. senatoria* larval frass collected and *Q. palustris* defoliation, 1990.

Chapter 8

Parasitism of orangestriped oakworm life stages in the urban landscape

Introduction

Numerous parasites of *Anisota senatoria* (J. E. Smith) (orangestriped oakworm), were reported to attack egg, larval, and pupal life stages. Hitchcock (1961c) suggested *A. senatoria* populations were kept below damaging levels by natural biological agents. Hitchcock (1958) reported 17 parasite species that attacked *A. senatoria*. Egg parasites included *Trichogramma pretiosa* (Riley) (Hymenoptera: Trichogrammatidae) and *Tetrastichus* sp. (Hymenoptera: Eulophidae). Fiske (1903) reported *Hyposoter fugitivus* (Say) (Hymenoptera: Ichneumonidae) as a larval parasite. Parasites that emerged from pupae included *Cratichneumon w-album* (Cresson) (Hymenoptera: Ichneumonidae) and *Winthemia datanae* (Townsend) (Diptera: Tachinidae). Arnaud (1978) listed 11 tachinid species from *A. senatoria*. Additional hymenopteran and dipteran parasites were included in Schaffner & Griswold (1934), Herting & Simmonds (1976), Riotte & Peigler (1981), and Peigler (1985).

The objectives of this study were to identify *A. senatoria* parasites and calculate parasite impact in the urban landscape.

Materials & Methods

Egg parasitism. In this study, *A. senatoria* egg masses were collected several days after egg eclosion. Langston (1957) collected egg masses of *Malacosoma* species after

eclosion to assess parasitism. Riotte & Peigler (1981) reported egg parasites emerged several days after *A. senatoria* eclosion. This was confirmed by placing two parasitized egg masses in an environmental chamber maintained at 27°C (L) and 21°C (D) and a photoperiod of 16:8 (L:D). Eggs were checked daily for *A. senatoria* eclosion and parasite emergence.

Egg masses were collected from *Quercus palustris* Muench., pin oak, and *Q. phellos* L., willow oak. Egg masses were collected from Norfolk in 1988-1990, Virginia Beach in 1989-1990, Chesapeake in 1989, and Gloucester Point, VA in 1990. Second generation egg masses were collected from Virginia Beach in 1989-1990. Individual egg masses were placed in 7.5 x 3.5 cm plastic boxes and held for 6 months at room temperature (about 24°C) for parasite emergence. The number of eclosed and parasitized eggs were counted from each egg mass. Parasitized eggs were determined by counting the number of discolored eggs and eggs with parasite emergence holes. Discolored eggs appeared black to grey compared with normal yellow eggs. All eggs that did not eclose and appeared to be parasitized were dissected and examined for parasite life stages.

Inundative release. The egg parasite used in this study, *Trichogramma minutum* (Riley) (Hymenoptera: Trichogrammatidae), was reared on *Sitotroga cerealella* (Oliver) (Lepidoptera:

Gelechiidae), Angoumois grain moth, by a commercial insectary (Rincon Vitova, Oak View, CA.). In 1989 laboratory experiments, 10 *Q. palustris* cuttings with egg masses on leaves were placed in 100 ml water-filled cups and placed in 10 plastic boxes (19 x 14 cm). Eight boxes received 4,200 *T. minutum* and two boxes received 8,400. A total of 50,400 *T. minutum* were exposed to 3,708 *A. senatoria* eggs for a parasite:host ratio of 13.6:1. Boxes were placed in the previously described environmental chamber. The number of parasitized eggs was determined after *A. senatoria* egg eclosion in July.

Inundative field releases of *T. minutum* were made in Norfolk, VA in 1989 and 1990. One *T. minutum* release was conducted on July 15, 1989, when the majority of *A. senatoria* eggs were freshly oviposited. Cards (6.54 cm^2) containing parasitized *S. cerealella* eggs were placed in 100 ml paper cups and attached to *Q. palustris* and *Q. phellos* trunks, 1.5 m above ground. A 1 cm hole was cut in cup bottoms to facilitate parasite emergence. Each card was estimated to have 4,200 *T. minutum* parasites with one parasite per *S. cerealella* egg. The number of *S. cerealella* eggs with *T. minutum* emergence holes was counted in a subsample of 7 cards to estimate parasite emergence. A total of 57 cards was placed in paper cups attached to 45 trees. A total of 239,400

T. minutum was released against 117,876 *A. senatoria* eggs for a parasite:host ratio of 2.0:1. *Anisota senatoria* eggs were collected the last week of July through the first week of August from each of the 45 trees and placed in 7.5 x 3.5 cm plastic boxes. Eggs were held for parasite emergence and parasitism determined.

In 1990, five releases of *T. minutum* were made. Release dates were July 8, 11, 13, 18, and 21 and coincided with the oviposition period of *A. senatoria* (Johnson & Lyons 1988). On each release date, 150 cards were placed on 75 *Q. palustris* and *Q. phellos* and 630,000 *T. minutum* were released. A total of 3.15×10^6 *T. minutum* was released against 141,780 *A. senatoria* eggs for a parasite:host ratio of 22.2:1.

Egg mass parasitism was calculated by dividing the number of parasitized egg masses by the number of egg masses collected from each location and year. Subsamples of parasitized egg masses were taken (Lashomb et al. 1987) and parasitism within an egg mass was determined by dividing the number of parasitized eggs by the number of eggs in each egg mass. Natural egg mortality was determined by dividing the number of desiccated eggs by the number of eggs in each egg mass. The number of egg masses and eggs that were parasitized by each of four egg parasites was determined. Some egg masses were parasitized by more than one parasite. Therefore, the

number of egg masses that were parasitized by at least each parasite species was reported. The number of egg masses and eggs parasitized by all four parasites were calculated.

Sex ratios of the two most abundant native egg parasites was determined. Sex ratios of *Aprostocetus* new sp. (Hymenoptera: Eulophidae) and *Anastatus hirtus* (Ashmead) (Hymenoptera: Eupelmidae) were determined by counting the number of adult males and females that had emerged. Adult male and female parasites that did not emerge were dissected from eggs and included in the sex ratio.

Larval parasitism. Larval parasitism was determined from examining groups of *A. senatoria* larvae for four years. The number of gregarious first and second instar was counted on *Quercus* in Norfolk and Virginia Beach, VA in July, 1987-1990. In 1990, additional locations were Chesapeake and Gloucester Point, VA. Second generation first and second instars were counted in Virginia Beach in late September, 1989-1990. *Anisota senatoria* populations were examined every two days for parasitized larvae, except Gloucester Point populations that were examined every two weeks. Parasitized larvae were placed in 3 x 5 cm laboratory boxes and held for parasite emergence. All parasitized larvae that had unemerged parasites were dissected and examined for parasite and hyperparasite life stages. Hyperparasites were determined from the presence of adult parasites and cocoons in addition to the primary larval

parasite and cocoon.

Pupal collections. Parasites that attacked *A. senatoria* larvae and emerged from pupae were recorded for five years. Fifth instar larvae were collected from defoliated trees as they migrated from tree trunks seeking suitable habitats to pupate. Larvae were collected from Norfolk in 1986-1990, Gloucester Point in 1987 and 1990, and Virginia Beach in 1989-1990. Second generation larvae were collected from Virginia Beach in 1990. Larvae were placed in 56 x 41 x 13 cm boxes with 8 cm of moist soil and allowed to pupate. Pupae were sexed according to characters described by Ehrlich et al. (1969). Parasitism was determined for each sex. Sexed pupae were separated into 19 x 14 x 10 cm closed boxes that were placed in the previously described environmental chambers. Pupae were moistened every few days to prevent dessication and examined daily for parasite emergence. Pupae that failed to eclose were dissected 1 year after collection and examined for parasite and hyperparasite life stages. In 1990, *A. senatoria* prepupae were placed in closed boxes in the previously described environmental chambers and examined daily for parasite emergence.

Parasitism was calculated by dividing the number of parasitized *A. senatoria* larvae and pupae by the number of larvae and pupae collected (Van Driesche 1983, Bastian & Hart 1990a, Daigle et al. 1990). Representative adult parasites

were sent to the USDA Systematic Entomology Laboratory in Beltsville, Md. and identified by the following: R. W. Carlson (Ichneumonidae), E. E. Grissell (Chalcididae, Eupelmidae, Perilampidae, and Pteromalidae), M. E. Schauff (Encyrtidae and Eulophidae), D. L. Vincent (Trichogrammatidae), and N. E. Woodley (Tachinidae). The eupelmid *Anastatus hirtus* (Ashmead) was identified by G. G. Gibson, Agriculture Canada, Biosystematics Research Centre, Ottawa, Canada and voucher specimens were deposited in Canadian National Collection. The eulophidae *Aprostocetus* new sp. was identified by J. LaSalle, International Institute of Entomology, London, U. K. Voucher specimens were deposited in the insect collection at the Hampton Roads Agricultural Experiment Station (HRAES).

Results and Discussion

Egg parasites. A subsample of two *A. senatoria* egg masses showed egg parasites emerged 5 and 7 days after *A. senatoria* eclosion. Therefore, collections of eclosed *A. senatoria* egg masses accurately sampled egg parasitism.

The most abundant egg parasite was *Aprostocetus* new sp. near *pandora* (Burks) (Hymenoptera: Eulophidae: Tetrastichinae) and was a new host record. This parasite was originally identified as *Tetrastichus* sp. by M. E. Schauff. The group is being revised by J. LaSalle and was placed in a different genus and identified as a new species. The only records of

Tetrastichus sp. parasitizing *A. senatoria* eggs were from Hitchcock (1961b) in Connecticut and Riotte & Peigler (1981) from *Anisota* sp. in Texas and South Carolina. The color description of *Tetrastichus* sp. given by Riotte & Peigler (1981) is similar for *Aprostocetus* n. sp. These unidentified species of *Tetrastichus* may be *Aprostocetus* n. sp. described in this study. *Aprostocetus* n. sp. was described by J. LaSalle (pers. com.) as near *A. pandora* that parasitized *Coloradia pandora* (Blake) (Lepidoptera: Saturniidae), pandora moth, eggs in Williamson River, Oregon (Burks 1943). However, *Aprostocetus* n. sp. had a more swollen antennal scape and funicular segments without distinct basal whorls of long setae when compared with *A. pandora* (J. LaSalle pers. com.). Male and female *Aprostocetus* n. sp. were easily distinguished by their color. Male *Aprostocetus* n. sp. were yellow-brown and females were black. One *Aprostocetus* n. sp. developed per *A. senatoria* egg.

Mean parasitism by *Aprostocetus* n. sp. varied between years and locations (Table 1). From 1988-1990, the percentage of egg masses that had parasitized eggs ranged from 0.0-77.7%, with a mean of 24.6%. Within parasitized egg masses, egg parasitization ranged from 3.4-18.8%, with a mean of 6.9%. Clausen (1940) reported a preponderance of females in the Tetrastichinae and similar results were found in this study. The mean sex ratio indicated twice as many female *Aprostocetus*

n. sp. were produced as males, with sex ratios from 1.8 to 5.7:1 (Table 1). Hitchcock (1961b) recorded *A. senatoria* egg parasitization by a related *Tetrastichus* species. He found 74.4% egg parasitization by *T. pretiosa* (Riley) and *Tetrastichus* sp. in one Connecticut location. He did not report percent parasitization by *Tetrastichus* sp. alone.

The second most abundant egg parasite was *Anastatus hirtus* (Ashmead) (Hymenoptera: Eupelmidae), a new host record. The Nearctic species of *Anastatus* need revision to better determine species limits and potential host ranges and the parasite reared from *A. senatoria* eggs appeared to belong to *A. hirtus* (G. Gibson, pers. com.). The only published host record for *A. hirtus* is *Thyanta custator* (F.) (Hemiptera: Pentatomidae) from New York, New Jersey, and Florida (Muesebeck et al. 1951, Peck 1963). Male and female *A. hirtus* were easily distinguished by their color. Male *A. hirtus* have metallic green heads and females are uniformly brown. Clausen (1940) reported all eupelmid egg parasites were solitary. One *A. hirtus* developed per *A. senatoria* egg. The only *Anastatus* sp. recorded from *Anisota* sp. (Burks 1958, Peck 1963) and *A. senatoria* eggs (Riotte & Peigler 1981) was *A. reduvii* (Howard). The species reared in this study was not *A. reduvii* (G. Gibson, pers. com.). Beal (1952) reported an unknown species of *Anastatus* in *A. senatoria* eggs from North Carolina.

Mean parasitism by *A. hirtus* varied between years and

locations (Table 1). From 1988-1990, the percentage of egg masses that had parasitized eggs ranged from 0.0-66.7%, with a mean of 11.7%. Within these parasitized egg masses, egg parasitization ranged from 1.6-9.2%, with a mean of 4.5%. The mean sex ratio indicated more male than female *A. hirtus* was produced, and ranged from 0.2 to 1.6:1 (Table 1).

Eggs oviposited on Virginia Beach trees in 1989-1990 and Gloucester trees in 1990 did not receive pesticide application and had high parasitism rates (Table 1). The highest egg mass parasitism by *Aprostocetus* n. sp. and *A. hirtus* occurred in eggs oviposited on trees located in Gloucester Point. The highest within egg mass parasitism by *Aprostocetus* n. sp. and *A. hirtus* occurred in first generation eggs oviposited on trees located in Virginia Beach in 1990. *Aprostocetus* n. sp. and *A. hirtus* were not affected by inundative *T. minutum* release in Norfolk areas. Parasitism rates were similar between *T. minutum* release and nonrelease areas in Norfolk, 1989-1990 (Table 1).

Inundative release. *Trichogramma minutum* was first reported as a gregarious endoparasite from *A. senatoria* eggs by Girault (1911). Laboratory experiments showed that egg mass parasitization by *T. minutum* was 100%. Within egg mass parasitization was 13.1%. These laboratory data indicated *T. minutum* was an effective egg parasite. A subsample of seven cards that contained *S. cerealella* eggs showed 92.2% were

parasitized by *T. minutum*. This high rate of successful *T. minutum* parasitism indicated parasites were emerging and available to parasitize *A. senatoria* eggs in 1989 and 1990 field releases.

Mean field parasitism by *T. minutum* was low for all years and locations (Table 1). From 1988-1990, the percentage of egg masses that had parasitized eggs ranged from 0.0-4.8%, with a mean of 2.3%. Within these parasitized egg masses, egg parasitization ranged from 0.5-1.5%, with a mean of 0.9%. The mean number of *T. minutum* per *A. senatoria* egg was 8.8±0.9 and ranged from 4-16. Langston (1957) reported a maximum of 22 *T. minutum* per *Malacosoma* sp. egg.

Data in this study suggested inundative releases of *T. minutum* were not effective in augmenting parasitism of *A. senatoria* eggs. Comparisons between Norfolk areas in 1989 that received one inundative *T. minutum* release and Norfolk areas in 1989 that had natural *T. minutum* populations showed only a 1.0% (4.8-3.8) increase in egg mass parasitism (Table 1). Within egg mass parasitism was slightly higher in eggs oviposited in trees that had natural *T. minutum* populations. Comparisons between Norfolk areas in 1990 that received five inundative *T. minutum* releases and Norfolk areas in 1990 that had natural *T. minutum* populations showed only a 1.8% (1.8-0.0) increase in egg mass parasitism (Table 1). Within egg mass parasitism was higher in eggs oviposited in trees that

had natural *T. minutum* populations. Egg mass parasitism was higher in trees that received one inundative release in 1989 compared with trees that receive five releases in 1990. This indicated parasite carryover from 1989 to 1990 was nonexistent. Smith (1988) found no *T. minutum* parasitism in years following inundative release and suggested harsh winters and lack of ecological diversity reduced availability of alternate hosts.

Several explanations can be proposed for the lack of increased parasitism in eggs oviposited on trees that received inundative releases. *Trichogramma minutum* has a wide host range (Muesebeck et al. 1951). Field parasitism by *T. minutum* was naturally low (Table 1) and *A. senatoria* eggs may have been nonpreferred hosts. Other caterpillar eggs in southeastern VA that are attacked by *T. minutum* in July include *Hyphantria cunea* (Drury) (Lepidoptera: Arctiidae), fall webworm, *Datana integerrima* (Grote & Robinson) (Lepidoptera: Notodontidae), walnut caterpillar, and *Heterocampa guttivitta* (Walker) (Lepidoptera: Notodontidae), saddled prominent. *Trichogramma* sp. was effective against *A. senatoria* eggs in Connecticut. Hitchcock (1961c) reported *T. pretiosa* field parasitism of *A. senatoria* eggs ranged from 23-59%. *Trichogramma minutum* is an arboreal species (Smith 1988) and may have dispersed from *Quercus* seeking more suitable host eggs. Smith (1988) found *T. minutum* dispersed a total of 18.5

m in 5 days and other *Trichogramma* sp. have been reported to disperse from 30.5 to 1,610 m (Jaynes & Bynum 1941, Stern et al. 1965). Other factors that may have affected *T. minutum* parasitism were habitat specificity, parasite competition, host cues, climatic conditions, and pesticide applications by homeowners. The laboratory reared *T. minutum* from the commercial insectary may have had poor survival in the field, had inferior host seeking, and lacked competitiveness. More laboratory and field experiments that examine *T. minutum* parasitism efficiency, release rates and timing, and suitability of commercially available species are needed.

Mean parasitism by *Ooencytrus* sp. (Hymenoptera: Encyrtidae) was not presented in Table 1 and only occurred in eggs sampled from Norfolk areas in 1989. Three *Ooencytrus* sp. were recovered from *A. senatoria* eggs. Egg masses that had parasitized eggs were 0.09%. Within parasitized egg masses, egg parasitization was 0.3%. This is a new host record for the genus, a common egg parasite (Muesebeck et al. 1951, Muesebeck & Burks 1967, Peck 1963).

Egg mass and within egg mass parasitism by *Aprostocetus* n. sp., *A. hirtus*, and *T. minutum* (Table 1) were not additive (parasitism rates by each species do not add to the total by all species) because egg masses were frequently attacked by more than one parasite. For example, *Aprostocetus* new sp. and *A. hirtus* were found parasitizing the same egg mass.

Individual eggs were attacked by only one parasite.

Second generation egg masses were not parasitized in 1989 and low egg mass parasitism occurred in 1990 for all egg parasites (Table 1). Egg parasites were not abundant during September and October when second generation *A. senatoria* eggs were being oviposited. A large sample size of 2288 egg masses from first and second generations was collected from 1988-1990. Combined egg mass parasitism by all four egg parasites (*Aprostocetus* n. sp., *A. hirtus*, *T. minutum*, and *Ooencytrus* sp.) ranged from 0.0-88.9% with a mean of 30.0%. Combined within egg mass parasitism by all four egg parasites ranged from 3.1-22.6% with a mean of 7.9%. Natural egg mortality from unhatched *A. senatoria* eggs, within parasitized egg masses, ranged from 0.3-2.6% with a mean of 1.7%. Natural mortality was higher than parasitism by *T. minutum*. These data showed a high proportion of egg masses were parasitized, but within egg mass parasitism was low. These four parasites were not abundant or effective in reducing *A. senatoria* populations.

Larval parasitism. The primary larval parasite was *Hyposoter fugitivus* (Say) (Hymenoptera: Ichneumonidae). Fiske (1903) and Muesebeck et al. (1951) described *H. fugitivus* as a solitary endoparasite of *A. senatoria* with a wide host range. This parasite primarily attacked the first three *A. senatoria* instars (Riotte & Peigler 1981). After *A.*

senatoria larval death, *H. fugitivus* larvae spun a silken cocoon affixed to the host larvae that split along the ventral surface (Langston 1957, Riotte & Peigler 1981). The cocoon adhered to the twig that contained the host (Felt 1905, 1926). These conspicuous cocoons and host larvae allowed for accurate determination of field parasitism. Percent parasitization by *H. fugitivus* ranged from 0.3-24.5% for first generation larval populations and 8.4-15.9% for second generation (Table 2). In 1989 and 1990, parasitization of first generation larvae was 0.9 and 5.4% and second generation parasitization was 15.9 and 8.4%, an 18 and 1.5-fold increase in parasitization respectively. First and second generation overall parasitization was 3.2 and 9.3%, a 3-fold increase.

First generation parasitism was low in this study (Table 2). Schaffner & Griswold (1934) reported only 1.9% *H. fugitivus* parasitization of *A. senatoria*. Webber & Schaffner (1926) reported *H. fugitivus* was the principal hymenopterous parasite of *A. senatoria* from 1915-1922 in New England. Barrows (1976) reported 30% parasitization of first generation *A. senatoria*. Second generation *A. senatoria* populations were first observed in the Virginia Beach location (HRAES) in 1989 and have been present ever since. *Hyposoter fugitivus* emerged from first generation *A. senatoria* larvae in August and normally overwintered in other hosts, possibly *H. cunea*, a common host throughout North America (Stoltz & Guzo 1986,

Ravlin & Haynes 1987). However, the availability of second generation *A. senatoria* in October of 1989 and 1990 allowed for a second *H. fugitivus* generation. The higher parasitism of second generation larvae may have been a behavioral adaptation by *H. fugitivus* to utilize a more readily available host. Many *H. fugitivus* pupae overwintered in *A. senatoria* second generation larvae.

One *A. senatoria* second generation larva was parasitized by *Apanteles* sp. (Hymenoptera: Braconidae) (Table 2), identified from the buff colored cocoons (Muesebeck 1921, Riotte & Peigler 1981, Peigler 1985). A total of five *Apanteles* cocoons was formed on one larvae but adults did not develop. The only species of this genus reported from *A. senatoria* is the gregarious *A. anisotae* (Muesebeck), first reported by Muesebeck (1921) from larvae collected in Falls Church, VA. Schaffner & Griswold (1934) reported only 0.5% parasitization of *A. senatoria* larvae by *A. anisotae*. The cocoon description indicated that the species in Table 2 could be *A. anisotae* (Muesebeck 1921). Riotte & Peigler (1981) reported *A. anisotae* from *A. senatoria* in Texas and the maximum number of parasites per host were ten.

Hyposoter fugitivus cocoons were exposed and vulnerable to parasites (Fiske 1903, Viereck 1916, Langston 1957). Langston (1957) reported 11 parasites of *H. fugitivus*. Eight parasites of *H. fugitivus* were collected from 1987-1990 (Table

3). The most abundant hyperparasite was *Ceratosmicra meteori* (Burks) (Hymenoptera: Chalcididae) (Table 3). Total hyperparasitization in first and second generation *A. senatoria* populations ranged from 2.9-49.1% and 23.7-27.8%, with overall means of 33.6 and 24.6% (Table 3). This high hyperparasitism decreased *H. fugitivus* populations and effectiveness as primary parasites. The overall mean number of *C. meteori* adults per *H. fugitivus* was 1.0, but two adult *C. meteori* emerged in each of 12 cocoons. *Ceratosmicra meteori* was recorded as solitary hyperparasites of *A. senatoria* through *H. fugitivus* collected in Maryland (Riotte & Peigler 1981). Grissell & Schauff (1990) reported *Ceratosmicra* sp. as hyperparasites of Lepidoptera and attacked Hymenoptera (Braconidae and Ichneumonidae). Hofmaster & Greenwood (1949) found that *Spodoptera frugiperda* (Smith) (Lepidoptera: Noctuidae), fall armyworm, populations controlled in VA by *Apanteles* sp.; but that *C. meteori* was a common hyperparasite.

Brachymeria ovata (Say) (Hymenoptera: Chalcididae) parasitized *H. fugitivus* reared from first generation *A. senatoria* larvae in 1987, 1988, and 1990 and was a new host record (Table 3). Total hyperparasitization ranged from 4.5-23.3%, with a mean of 5.9%. Upon dissection of some *H. fugitivus* cocoons, *B. ovata* adults and pupal cases were found. There was one *B. ovata* per *H. fugitivus* cocoon. These data

indicated *B. ovata* was a solitary parasite that attacked *H. fugitivus*. *Brachymeria ovata* was not previously recorded from *A. senatoria* or *H. fugitivus* (Muesebeck et al. 1951, Peck 1963, Riotte & Peigler 1981), but is a primary pupal parasite of a wide range of Lepidoptera and Diptera species (Grant & Shepard 1987). *Brachymeria ovata* was described as a successful, widespread polyphagous species but data were lacking on adaptations and biology (E. E. Grissell, pers. com.).

Gelis tennellus (Say) (Hymenoptera: Ichneumonidae) parasitized *H. fugitivus* reared from second generation *A. senatoria* larvae in 1989 and 1990. Mean hyperparasitization was 2.2% (Table 3). *Gelis tennellus* hyperparasitism of *A. senatoria* probably did not significantly reduce *H. fugitivus* populations. It was recorded from *H. fugitivus* (Viereck 1916, Muesebeck et al. 1951, Langston 1957, Riotte & Peigler 1981) as a solitary parasite with a wide host range. Doner (1936) documented the biology of *G. tennellus* and Muesebeck & Dohanian (1927) stated four generations per year occurred and males were unknown.

The solitary hyperparasite *Eupelmus cyaniceps* (Ashmead) (Hymenoptera: Eupelmidae) was a new host record and was only collected from Chesapeake, VA in 1990 (Table 3). Overall mean hyperparasitization was 0.5%. One adult *E. cyaniceps* emerged per *H. fugitivus* cocoon. This species was reported as an

effective primary parasite of the boll weevil (Pierce 1908), but was not previously recorded from *A. senatoria* or *H. fugitivus* (Muesebeck et al. 1951, Peck 1963). Species of *Eupelmus* showed diversity in habit and attacked Diptera gallformers, Coleoptera and Diptera in plant stems and flower heads, Lepidoptera, Orthoptera eggs, and were facultatively hyperparasitic (Clausen 1940, Grissell & Schauff 1990).

Pteromalus sp. (Hymenoptera: Pteromalidae) was only collected from second generation *A. senatoria* larvae in 1990 and overall mean hyperparasitization was 2.0% (Table 3). The mean number of adults per *H. fugitivus* cocoon was 1.9. *Pteromalus* sp. was described as a gregarious endoparasite that acted as a primary parasite or hyperparasite of Coleoptera, Diptera, Hymenoptera, and Lepidoptera (Clausen 1940). The only species recorded from *H. fugitivus* was *P. puparium* (Muesebeck et al. 1951, Peck 1963), a common parasite throughout Canada and the United States. Fiske (1903) first reported *P. puparium* as a parasite of *H. fugitivus* reared from *Malacosoma americanum* (F.) (Lepidoptera: Lasiocampidae), eastern tent caterpillar. The *Pteromalus* sp. reported in Table 3 may be *P. puparium*, but the group requires revision and species are difficult to identify (E. E. Grissell pers. com.).

Three adult *Perilampus* spp. (Hymenoptera: Perilampidae) were collected from three *H. fugitivus* cocoons for an overall

mean parasitization of 0.2% (Table 3). The Perilampidae is being revised and specimens were not identified to species (E. E. Grissell pers. com.). The only *Perilampus* sp. reported from *H. fugitivus* was *P. hyalinus* (Say) (Muesebeck et al. 1951, Langston 1957, Peck 1963), collected from *A. senatoria* pupae (Table 4), and the *Perilampus* sp. recorded from *H. fugitivus* cocoons (Table 3) was probably *P. hyalinus*.

Isdromas lycaenae (Howard) (Hymenoptera: Ichneumonidae) was collected from *H. fugitivus* in second generation *A. senatoria* larvae in 1990, for an overall parasitization rate of 4.5% (Table 3) and was a new host record. *Isdromas lycaenae* was a solitary parasite except one *H. fugitivus* cocoon that yielded two adults. This ichneumonid was reported as a parasite of *H. fugitivus* reared from *Anisota peigleri* (Riotte) in North Carolina (Riotte & Peigler 1981), South Carolina, and Texas (Peigler 1985). Both the Ichneumonidae and Chalcididae showed diversity and adaptability in parasitic habits and multiple hyperparasitism was reported (Clausen 1940). Multiple hyperparasitism by *I. lycaenae* and *C. meteori* was found in four *A. senatoria* dissected larvae. In two of the four larvae, *I. lycaenae* emerged successfully and dead *C. meteori* adults were found inside. This suggested *C. meteori* reached the prepupae stage, was parasitized by *I. lycaenae*, emerged as an adult, and died. In the other two larvae, both *I. lycaenae* and *C. meteori* adult remains were found inside *H.*

fugitivus. This indicated *I. lycaenae* did not successfully emerge after parasitizing *C. meteori*. Furthermore, there was the possibility that both *I. lycaenae* and *C. meteori* parasitized *H. fugitivus*, pupated, but did not emerge.

Two adult *Horismenus* sp. near *lixivorous* (Crawford) (Hymenoptera: Eulophidae) were collected from *H. fugitivus* in second generation *A. senatoria* larvae and the collection was a new host record (Table 3). Overall mean hyperparasitization was 0.1%. The mean number of adults per *H. fugitivus* cocoon was 2.0. The U. S. National Collection had no comparable identified specimens reared from *H. fugitivus* (M. E. Schauff, pers. com.). *Horismenus* sp. was not recorded from *H. fugitivus* (Muesebeck et al. 1951, Peck 1963), and was a primary parasite of Bruchidae. Other species were primary or secondary parasites of Lepidoptera (Burks 1971). *Horismenus lixivorous* was found in Texas and Arizona as a primary parasite of Curculionidae (Burks 1971). Riotte & Peigler (1981) reported that *H. floridanus* (Ashmead) was a solitary parasite of *Apanteles anisotae* reared from *Anisota* sp. in Texas. Burks (1971) reported *H. floridanus* was distributed from New Jersey south to Florida and Texas.

Hyperparasitism of first and second generation larvae was higher in 1988 and 1990 (Table 3). Parasites that had the greatest impact on *H. fugitivus* were *C. meteori*, *B. ovata*, and *I. lycaenae*. These three hyperparasites accounted for 87% of

all species collected. Hyperparasitization of first and second generation larvae by all species was 40.0 and 33.6%. This high degree of hyperparasitism decreases the ability of *H. fugitivus* to significantly impact *A. senatoria* populations.

Pupal collections. Eleven tachinid species have been reported from *A. senatoria* (Arnaud 1978), but only three were recovered from 2,440 pupae and prepupae collected from 1986-1990 (Table 4). These tachinid parasites attacked *A. senatoria* larvae but emerged from pupae. The proportion of larvae parasitized and identified as male and female upon pupation was approximately equal. Therefore, results from male and female pupae were combined (Table 4).

Lespesia anisotae (Webber) was the most abundant and effective parasite (Table 4). During 1986-1990, parasitization of first generation larvae ranged from 2.1-30.8%. Larvae collected from trees in Norfolk in 1987 and Gloucester Point in 1990 experienced the highest *L. anisotae* parasitism (Table 4). Overall mean parasitization was 10.7%. Parasitization of second generation larvae was 22.9% (Table 4). One *L. anisotae* per *A. senatoria* pupa was found in this study. Schaffner & Griswold (1934) reported one or possibly two *L. anisotae* were found per host. *Lespesia anisotae* was first described by Webber (1930) from *A. senatoria* collected in New Jersey. Schaffner & Griswold (1934) found only 2.1% *A. senatoria* were parasitized by *L. anisotae*. Adult *L. anisotae*

were observed in July over the past 5 years and oviposited on gregarious groups of first and second instar larvae. Beneway (1963) reported *Lespesia* sp. deposited membranous eggs on the body of their hosts. Schaffner & Griswold (1934) reported *L. anisotae* adults were present from July to August with one generation per year. *Lespesia anisotae* maggots overwintered in host pupae and emerged in the spring (Riotte & Peigler 1981, Schaffner & Griswold 1934). Puparia were formed in the soil and adults emerged in the summer (Riotte & Peigler 1981, Schaffner & Griswold 1934). Of the 251 *L. anisotae* puparia collected from 1986-1990 (Table 4), 248 pupated outside *A. senatoria* pupae and 3 or 1.2% pupated inside.

Belvosia bifasciata (F.) was recovered in small numbers in 1987, 1989, and 1990 (Table 4). During these years, parasitization of first generation larvae ranged from 0.2-3.9%. Larvae collected from trees in Virginia Beach experienced the highest *B. bifasciata* parasitism (Table 4). Overall mean parasitization was 0.7%. Parasitization of second generation larvae was 2.1% (Table 4). One *B. bifasciata* per *A. senatoria* pupa was found in this study. *Belvosia bifasciata* was reported from a wide range of hosts (Arnaud 1978). It was first reported from *A. senatoria* in North Carolina (Brimley 1922) and later in Texas by Riotte & Peigler (1981). These large flies searched for *A. senatoria* larvae in the fall and were solitary parasites (Riotte &

Peigler 1981). Maggots pupated inside *A. senatoria* hosts (Riotte & Peigler 1981). Multiple parasitism by *L. anisotae* and *B. bifasciata* was observed in this study but neither species survived. Of the 268 parasitized *A. senatoria* pupae, two or 0.7% had both *L. anisotae* and *B. bifasciata* life stages present.

The only parasite that has been recovered from *L. anisotae* and *B. bifasciata* was *Perilampus hyalinus* (Say) (Hymenoptera: Perilampidae) (Table 4) and these were new host records (Muesebeck et al. 1951). Parasitization of *L. anisotae* occurred only in larvae collected from Gloucester Point in 1990, with a mean of 8.2% (Table 4). The proportion of *A. senatoria* larvae hyperparasitized, and identified as male and female upon pupation was higher in males (10.2%) compared with females (4.5%). Mean parasitism of *L. anisotae* by *P. hyalinus* was 2.0% from 1986-1990 (Table 4).

Parasitism of *B. bifasciata* occurred only in female *A. senatoria* pupae collected in Gloucester Point, 1987 and 1990. Total hyperparasitization was 100.0 and 15.4%. Parasitization of *B. bifasciata* was greater than *L. anisotae* from 1986-1990, with means of 23.5 and 2.0%, respectively (Table 4). *Perilampus* sp. was reported as hyperparasitic on Lepidoptera through Diptera and Hymenoptera primary parasites (Clausen 1940, Grissell & Schauff 1990). In the subfamily Perilampinae, eggs were oviposited on plant parts and eclosed

planidia waited for hosts (Grissell & Schauff 1990). Planidia entered the host and searched for a tachinid or ichneumonid parasite. Planidia entered the parasite, waited for parasite pupation, then emerged and fed externally on the parasite. In the field, perilampid planidia feed and develop in the spring (Clausen 1940). The biology of *P. hyalinus*, a parasite on a tachinid host, *Ernestia ampelus* (*mericia*) (Walker), was well documented by Smith (1912).

Three *Lespesia aletiae* (Riley) adults were recovered in second generation *A. senatoria* prepupae in 1990, the only year prepupae were examined for parasites (Table 4). This was a new host record for *L. aletiae* (Arnaud 1978). Maggots pupated outside *A. senatoria* hosts and one *L. aletiae* emerged per prepupa. *Lespesia aletiae* has been reported from a wide range hosts, including the Saturniidae (Arnaud 1978). Schaffner & Griswold (1934) reported *L. aletiae* adults were present from May to October and had two or more generations per year. The overwintered life stage was unknown and *L. aletiae* was solitary (Schaffner & Griswold 1934).

Parasitization of first generation larvae by *L. anisotae* and *B. bifasciata* was high at 17.9% in 1986, decreased in 1987-1988 to 10.5 and 2.4%, increased in 1989-1990, and peaked at 21.7% in 1990. Parasitization of first and second generation larvae in 1990 was approximately equal (21.7 and 25.0%). During this 5 year study, *Lespesia anisota* and *B.*

bifasciata had a mean parasitization of 11.4%, and 3.3% were parasitized by *P. hyalinus*. The overall dipteran parasitism (11.4%) was higher than hymenopteran parasitism (5.9%, Table 2). However, dipterans were less effective *A. senatoria* parasites than the hymenopterans. Larvae parasitized by dipterans fed and defoliated *Quercus*, and *A. senatoria* death only occurred in the pupal stage. These dipterans decreased survival of overwintering *A. senatoria* pupae and consequent summer populations.

In this study, a high proportion of *A. senatoria* egg masses was found to be parasitized by four egg parasites, but within egg mass parasitism was low. Inundative releases of *T. minutum* did not increase parasitism rates. First and second generation larval parasitism by *Hyposoter fugitivus* and *Apanteles* sp. was low. Eight hyperparasites of *A. senatoria* decreased the effectiveness of larval parasites. Diptera parasitism of larval *A. senatoria* by *Lespesia anisotae*, *L. aletiae*, and *Belvosia bifasciata* was higher than parasitism by Hymenoptera. One parasite of *L. anisotae* and *B. bifasciata* was found. These data suggested *A. senatoria* parasites in southeastern VA were not as abundant as in other areas of the country. Hitchcock (1961c) stated *A. senatoria* populations in Connecticut were kept below damaging levels by natural biological agents. *Anisota senatoria* populations have been consistently high since 1985 and have caused significant

defoliation (Coffelt & Schultz 1991c). Southeastern VA is surrounded by water, and heavy pesticide pressure from mosquito abatement programs may decrease native parasite populations. This lack of native parasites has undoubtedly contributed to high *A. senatoria* populations in southeastern VA.

Table 1. Mean percent parasitism of *A. senatoria* egg masses and within parasitized egg masses, 1988-1990.

			Mean % egg masses with parasitized eggs				Mean % of eggs parasitized within egg masses				Mean % natural egg mortality	Mean sex ratio F:M	
Loc[t]	Year	No. of egg masses	Apr[u]	Ah[v]	Tm[w]	all sp.[x]	Apr	Ah	Tm	all sp.		Apr	Ah
Norf	1988	244	19.7	11.8	0.4	22.9	3.4	3.9	0.7	5.8	1.9	3.5:1	0.2:1
Norf	1989	341	34.3	14.4	3.8	37.5	5.5	3.9	0.8	6.7	1.4	2.5:1	0.2:1
Norf[y]	1989	418	34.0	15.8	4.8	39.4	4.4	3.4	0.9	5.3	1.5	2.5:1	0.3:1
VaB	1989	329	2.1	1.8	1.5	5.2	18.8	2.0	0.6	8.6	1.2	2.8:1	0.9:1
VaB[z]	1989	15	0.0	0.0	0.0	0.0					1.6		
Ches	1989	158	2.5	1.3	1.3	5.0	8.3	1.6	0.9	4.8	2.6	5.7:1	1.2:1
Norf	1990	120	24.1	16.6	0.0	33.3	15.5	5.8		13.1	2.2	2.4:1	0.3:1
Norf[y]	1990	510	37.5	13.5	1.8	42.7	7.7	5.0	1.5	8.5	1.6	1.8:1	0.4:1
VaB	1990	18	38.8	50.0	0.0	55.5	17.1	9.2		22.6	1.7	2.6:1	1.0:1
VaB[z]	1990	117	2.5	4.3	2.5	9.4	4.1	4.0	0.5	3.1	2.0	2.0:1	1.6:1
Gloc	1990	18	77.7	66.7	0.0	88.9	16.7	8.4		21.0	0.3	1.8:1	0.4:1
Total or Mean		2288	24.6	11.7	2.3	30.0	6.9	4.5	0.9	7.9	1.7	2.2:1	0.4:1

[t]Locations; Norf=Norfolk, VaB=Virginia Beach, Ches=Chesapeake, Gloc=Gloucester Point, VA.
[u]Egg masses and eggs that contained *Aprostocetus* n. sp.
[v]Egg masses and eggs that contained *Anastatus hirtus*.
[w]Egg masses and eggs that contained *Trichogramma minutum*.
[x]Egg masses and eggs that contained *Aprostocetus* n. sp., *Anastatus hirtus*, *Trichogramma minutum*, and *Ooencytrus* sp.
[y]Norfolk *Trichogramma minutum* release areas.
[z]Second generation *A. senatoria* eggs were sampled.

Table 2. Mean percent larval parasitism of *A. senatoria* first and second generations, 1987-1990.

Loc[t]	Year	% parasitization *Hyposoter fugitivus*	N[u]	*Apanteles* sp.	N	Total parasitization in each year for each generation	N[v]
Norf	1987	14.1	7				
VaB	1987	2.8	23			3.4	860
Norf	1988	4.2	100				
VaB	1988	1.1	16			3.1	3784
Norf	1989	8.8	48				
VaB	1989	0.3	19			0.9	7587
VaB[w]	1989	15.9	311	0.05	1	15.9	1960
Norf	1990	1.2	11				
VaB	1990	5.9	103				
Ches	1990	5.1	276				
Gloc	1990	24.5	57			5.4	8278
VaB[w]	1990	8.4	1193			8.4	14267
Total	87-90					3.2	20509
	89-90[w]					9.3	16227

[t]Locations: Norf=Norfolk, VaB=Virginia Beach, Ches=Chessapeake, Gloc=Gloucester Point, VA.
[u]Number of parasitized *A. senatoria* larvae.
[v]Total number of *A. senatoria* host larvae.
[w]Second generation *A. senatoria* larvae.

Table 3. Mean percent hyperparasitism of *A. senatoria* larvae, 1987-1990.

				Mean % parasitization of *Hyposoter fugitivus* by each species[t]											
Loc[u]	Yr	Cm	N[v]	Bo	N	Gt	N	Ec	N	Pt	N	Pe	N	Il	N	Hl	N
Norf	1987			100.0	7												
Total[w]				23.3	7												
Norf	1988	57.0	57	12.0	12												
Total		49.1	57	10.3	12												
Norf	1989	4.1	2														
Total		2.9	2														
VaB[x]	1989	27.8	87			0.6	2									0.3	1
Norf	1990	9.0	1														
VaB	1990	24.2	25														
Ches	1990	43.8	121	4.0	11			1.1	3								
Gloc	1990	28.0	16	15.8	9												
Total		36.4	163	4.5	20			0.7	3								
VaB[x]	1990	23.7	283			2.6	31			2.4	29	0.3	3	5.6	67	0.08	1
Total[y]		33.6	222	5.9	39			0.5	3								
Total[z]		24.6	370			2.2	33			2.0	29	0.2	3	4.5	67	0.1	2

[t]Parasites: Cm=*Ceratosmicra meteori*, Bo=*Brachymeria ovata*, Gt=*Gelis tennellus*, Ec=*Eupelmus cyaniceps*, Pt=*Pteromalus* sp., Pe=*Perilampus* sp., Il=*Isodramas lycaenae*, Hl=*Horisemenus* sp. nr. *lixivorus*.
[u]Locations: Norf=Norfolk, VaB=Virginia Beach, Ches=Chesapeake, Gloc=Gloucester Point, VA.
[v]Number of *Hyposoter fugitivus* parasitized.
[w]Total includes all locations in that year.
[x]Second generation *A. senatoria* larvae.
[y]Total hyperparasitism for the first generation.
[z]Total hyperparasitism for the second generation.

Table 4. Mean percent tachinid parasitism and *Perilampus hyalinus* hyperparasitism ( ) of *A. senatoria* larvae, 1986-1990.

		Mean % parasitization by each species[u] (*P. hyalinus* % parasitization)					
Loc[v]	Yr	La	N[w]	Bb	N	Ll	N
Norf	1986	17.9	90				
Norf	1987	30.8	4				
Gloc	1987	4.1	3	2.7	2		
				(100.0	2)		
Total[x]	1987	8.1	7	2.3	2		
				(100.0	2)		
Norf	1988	2.4	8				
Norf	1989	11.7	71	0.1	1		
VaB	1989	2.1	10	0.2	1		
Total	1989	7.6	81	0.2	2		
VaB	1990	2.6	4	3.9	6		
Gloc	1990	29.9	61	3.4	7		
		(8.2	5)	(28.6	2)		
Total	1990	18.1	65	3.6	13		
		(7.7	5)	(15.4	2)		
VaB[y]	1990	22.9	11	2.1	1		
VaB[z]	1990					6.5	3
Grand Total 1st gen.	86-90	10.7 (2.0	251 5)	0.7 (23.5	17 4)		

[u]Parasites: La=*Lespesia anisotae*, Bb=*Belvosia bifasciata*, Ll=*Lespesia aletiae*.
[v]Locations: Norf=Norfolk, VaB=Virgnia Beach, Gloc=Gloucester Point, VA.
[w]Number of parasitized pupae or parasitized *L. anisotae* and *B. bifasciata* (N).
[x]Total includes all locations in that year.
[y]Second generation *A. senatoria* pupae.
[z]Second generation *A. senatoria* prepupae.

Chapter 9

Host plant preference of the orangestriped oakworm

Introduction

Beck & Schoonhoven (1980) defined host plant preference by insects as a behavioral response in which some plants within an insect's host plant range were selected over others. Identifying the least preferred host plants and insect-resistant trees and shrubs were considered important components of an integrated pest management (IPM) (Morgan et al. 1978). Host plant preference was documented for several important shade tree pests including the Asiatic oak weevil (Ferguson et al. 1991), gypsy moth (Barbosa et al. 1983, Peterson & Smitley 1991), and carpenterworm (Solomon 1988). Cultivar preference for urban landscape trees and shrubs by the mimosa webworm (Bastian & Hart 1990b) and hawthorn lace bug (Schultz & Coffelt 1987) were identified. Preference factors commonly evaluated include larval survival, development rate, consumption, longevity, pupal weight, oviposition, fecundity, and defoliation.

Anisota senatoria J. E. Smith (orangestriped oakworm), preferred *Quercus* (oak) species but feeds on *Betula* (birch) (Dimmock 1885, Headlee 1918), *Acer* (maple), *Corylus* (hazelnut), and *Carya* (hickory) species (Houser 1918, Becker 1938). Hitchcock (1961b) found *A. senatoria* larvae fed and developed on any kind of *Quercus* but that there was a preference among species. Herrick (1935) reported *A. senatoria* preferred *Q. alba* (L.) (white oak), and *Q.*

ilicifolia (Wangenh.) (scrub oak), although Hitchcock (1961b) found preference for *Q. velutina* (Lam.) (black oak) rather than *Q. alba*. Lawson et al. (1982) measured several *A. senatoria* growth indices of larvae reared on six *Quercus* species and found growth was not significantly different between species.

The objectives of this study were to identify *A. senatoria* preference among *Quercus* species and determine tree susceptibility.

Materials and Methods

1987-1989 field experiments. Eleven *Quercus* species were planted in November, 1985, in a completely randomized design (CRD) at the Hampton Roads Agricultural Experiment Station (HRAES), Virginia Beach, VA. In July, 1987, 25 first instar *A. senatoria* were placed on an individual leaf of nine *Quercus* species. The nine *Quercus* species used were: *Q. acutissima* Carruth., sawtooth oak; *Q. alba* L., white oak; *Q. bicolor* Willd., swamp white oak; *Q. coccinea* Michx., scarlet oak; *Q. falcata* Michx., southern red oak; *Q. macrocarpa* Michx., bur oak; *Q. palustris* Muenchh., pin oak; *Q. prinus* L., chestnut oak; and *Q. rubra borealis* (Michx. f.) Farw., northern red oak. Six replications of all species were used except three and seven replications for *Q. falcata* and *Q. rubra borealis*, respectively. Larvae were examined daily and the date of 60% larval molting to the next instar, the number of live larvae,

and number of leaves consumed per tree were recorded. Development, survival in each instar, and leaf area consumed per larva was determined. Percent survival was based on the number of live larvae entering each stage. Larvae were categorized into early instars (first-third), late instars (primarily fourth) and fifth instars. Two representative leaves per tree were collected and leaf areas (cm^2) measured with a video analysis device (Skye Instruments, Quakertown, PA), described by Hough-Goldstein et al. (1991).

In July, 1988, eggs were pinned on leaf undersides of 11 *Quercus* species. Upon egg eclosion, 50 larvae were established per tree. Four replications of *Q. phellos* L., willow oak, were included. The number of tree replicates for the remaining trees were five *Q. falcata*, nine *Q. alba* and *Q. macrocarpa*, and ten *Q. acutissima*, *Q. bicolor*, *Q. coccinea*, *Q. palustris*, *Q. prinus*, and *Q. rubra borealis*. Development and survival in each instar was determined.

In July, 1989, one egg mass was pinned on leaf undersides of the same 11 *Quercus* species. Only one *Q. nigra* had adequate foliage, but was not included in data analysis due to lack of replication. Defoliation was assessed (Coffelt & Schultz 1990b) on August 10 and the number of larvae surviving to late fourth-fifth instars was determined. The number of tree replicates varied from four to ten (Table 2).

1990 laboratory experiments. *Anisota senatoria* eggs were pinned on leaf undersides of 11 *Quercus* species cuttings. Upon egg eclosion, five larvae were established per cutting. Cuttings were placed in 100 ml water-filled cups placed in 19 x 11 cm plastic boxes. Boxes were placed in an environmental chamber maintained at 26.4°C (L) and 21°C (D) and a photoperiod of 16:8 (L:D). Five replications per species were maintained with exception of *Q. prinus* and *Q. macrocarpa* that had four replications. Larvae were examined daily and the date of 60% larval molting to the next instar and the number surviving to the fifth instar was recorded. Instar development time on each *Quercus* species was determined. A 3 cm soil layer was placed in the boxes for pupation. Larvae that successfully pupated were weighed to the nearest 0.01 g and pupae were sexed (Ehrlich et al. 1969).

1990 larval preference. Thirty *A. senatoria* eggs were placed in the middle of a circular plastic container that was 18 cm in diameter and 8 cm in depth. Circular leaf disks (533 mm^2) were cut from each of 11 *Quercus* species leaves in July and randomly placed in a circle around *A. senatoria* eggs. All leaf disks were taken from mature leaves (young growth was not sampled) on the same day; therefore, leaf age was appoximately the same for all species. Eggs were prevented from desiccating by placing moist paper towels on container bottoms

and covering containers. Upon egg eclosion, 25 larvae were established per container. This experiment was repeated with 25 second instars per container. There were eight containers of first and second instars. Containers were placed in the previously described environmental chambers. After 48 hours of feeding, larvae and leaf disks were removed. The area consumed on each leaf disk was determined by the previously described video device (Skye Instruments, Quakertown, PA).

1990-1991 ovipositional preference. Trees that were planted in 1985 in a completely randomized design (CRD) were used in 1990 and 1991 field experiments. Trees were planted 6 m apart in mulched rows separated by 2 m of mowed grass. There were 12 rows of trees and each row had 11 different tree species. Trees were replaced when tree mortality occurred. In 1990, five trees were dead and a total of 126 trees were available for *A. senatoria* oviposition.

In 1990, virgin female and male moths were collected each morning during the last week of June and the first week of July as they emerged from overwintering pupae. Moths were collected in Norfolk, VA, from lawns that had either *Q. phellos* or *Q. palustris* trees. Moths were placed in screened cages, transported to the CRD plot, and released every 6 m in the grass area between rows. Gravid females were poor fliers (Lintner 1889) and crawled up tree trunks and oviposited on leaves attached to lower limbs. Twelve female and eight male

moths were released in each of 11 grass areas between rows. The number of egg masses and the number of eggs per mass per tree were counted during the last week of July.

In 1991, oviposition was determined from *A. senatoria* populations that overwintered at the HRAES. Moths were observed ovipositing on trees in the CRD plot during early July. The number of egg masses per tree was counted during the last week of July.

Data were subjected to analysis of variance (ANOVA) and differences between means were tested for significance ($P<0.05$) with the Waller-Duncan *k* ratio procedure (*k* ratio=100) (SAS Institute 1985). Arcsin transformation was performed on percent survival data to maintain homogeneity of variance (Steel & Torrie 1980).

Results and Discussion

1987-1989 field experiments. In 1987 field experiments, high larval mortality occurred and percent survival by instar was not significantly different ($P>0.05$) among the nine *Quercus* species. Only larvae reared on *Q. palustris*, *Q. coccinea*, and *Q. macrocarpa* survived to the fifth instar. Survival was 8.0, 4.6, and 1.3%, respectively. Development time in each instar was not significantly different ($P>0.05$) between *Quercus* species. The low populations of 25 larvae experienced high mortality (Chapter 5) and few survived past the second instar.

Larval consumption was not significantly different (P>0.05) and highly variable among *Quercus* species. Total leaf area consumed was highest for larvae reared on *Q. palustris* and *Q. coccinea*. Mean consumption per larva was calculated on the only three *Quercus* species that supported *A. senatoria* populations to the fifth instar (Table 1). Mean consumption was highest on *Q. coccinea* compared with *Q. palustris* and *Q. macrocarpa*. Fifth instars consumed 85.1% of the *Q. coccinea*, *Q. palustris* and *Q. macrocarpa* foliage, late instars 13.2%, and early instars 1.6% (Table 1). Frass data indicated that fourth and fifth instars produced 92% of the total frass produced by an average *A. senatoria* larval group (Chapter 6).

In 1988 field experiments, high larval mortality occurred and survival by instar was not significantly (P>0.05) between the 11 *Quercus* species. Only larvae reared on *Q. palustris*, *Q. bicolor*,and *Q. alba* survived to the fifth instar. Survival was 9.2, 3.1, and 1.7%, respectively. Development in each instar was not significantly different (P>0.05) between species and 1987 and 1988 data were pooled. Instar development in days and number of tree replicates (N) were as follows: first, 8.0±0.06 (55); second, 7.3±0.2 (27); third, 6.8±0.4 (11); fourth, 5.9±0.4 (8); and fifth, 4.8±0.4 (7).

In 1989 field experiments, mean defoliation was significantly higher on *Q. coccinea*, *Q. rubra borealis*, and *Q.*

palustris compared with *Q. prinus*, *Q. acutissima* and *Q. macrocarpa* (Table 2). Solomon et al. (1980) reported forest stands of *Q. rubra* and *Q. alba* on upland sites were the most heavily defoliated by *A. senatoria*. *Quercus alba* had an intermediate level of defoliation in this study (Table 2). In Norfolk, VA, 100% defoliation of *Q. palustris* was observed by natural populations of *A. senatoria* but adjacent *Q. alba* were 0% defoliated (unpublished data). Survival of *A. senatoria* was not significantly different ($P>0.05$) between *Quercus* species (Table 2). Higher survival occurred for larvae reared on *Q. coccinea* and *Q. acutissima*.

1990 laboratory experiments. Development was significantly accelerated for larvae reared on *Q. palustris* and *Q. macrocarpa* in three of the five instars and for *Q. phellos* and *Q. coccinea* in two of the five instars (Table 3). Slower development occurred for larvae reared on *Q. nigra* and *Q. alba* in four of the five instars (Table 3). Field experiments showed development was not significantly different between *Quercus* species; however, because of favorable laboratory conditions, true developmental effects were isolated and significant differences in species were detected. Volney et al. (1983) found differences occurred in laboratory and field developmental rates.

Frass was measured and weighed from larvae reared on the 11 *Quercus* species (Chapter 7). Frass length was longer

(Chapter 7) in species that also had accelerated development (Table 3). Slower development occurred for larvae reared on *Q. alba* and frass lengths were significantly shorter. However, the opposite relationship was found for larvae reared on *Q. nigra*. Slower development occurred for larvae reared on *Q. nigra*, but frass lengths were significantly longer. *Quercus nigra* may have unique leaf qualities and chemistry that caused changes in frass length.

Larvae reared on *Q. macrocarpa* had significantly lower survival than six of the 11 *Quercus* species (Table 4). Higher survival occurred for larvae reared on *Q. coccinea*, *Q. acutissima*, *Q. alba*, *Q. rubra borealis*, *Q. palustris*, and *Q. phellos*. Female pupal weight was significantly higher for larvae reared on *Q. acutissima*, *Q. coccinea*, *Q. palustris* and *Q. rubra borealis* than larvae reared on *Q. falcata* (Table 4). Male pupal weight was not significantly different ($P>0.05$) between species.

1990 larval preference. In choice tests, leaf area consumed by first and second instar *A. senatoria* was not significantly different ($P>0.05$) among 11 *Quercus* species (Table 5). Consumption was variable and standard errors were high (Table 5). Leaf consumption by first instars ranged from 84.7 ± 47.5 mm^2 on *Q. alba* to 0 mm^2 on *Q. rubra borealis* and *Q. macrocarpa*. Mean first instar consumption on all *Quercus*

species was 24.1±5.8 mm^2 or 4.5% of the leaf disks. Second instar consumption ranged from 161.1±34.9 mm^2 on *Q. nigra* to 15.3±10.2 mm^2 on *Q. bicolor*. Mean second instar consumption on all *Quercus* species was 99.3±13.7 mm^2 or 18.6% of the leaf disks. These experiments were repeated with third instars but within 24 hours all *Quercus* species leaf disks were consumed.

Pubescence was a factor in early instar preference. Pubescent leaves have been reported from *Q. falcata*, *Q. macrocarpa* and *Q. prinus* trees (Bailey & Bailey 1976). Leaf disk consumption by first instars was low on pubescent leaves from *Q. prinus* and none on *Q. macrocarpa*. Second instar consumption was low on *Q. macrocarpa*. *Quercus falcata* pubescent leaves were intermediate in terms of their consumption by larvae. Riotte & Peigler (1981) observed pubescent leaves were less preferred by early instar *Anisota* species.

1990-1991 ovipositional preference. Preference was evaluated by counting the number of *Quercus* species available for oviposition in the CRD plot, and the number of egg masses and eggs per egg mass were divided by the number of trees per *Quercus* species available. Therefore, the number of egg masses and eggs per egg mass were low compared with other studies (Chapter 4). This procedure provided an accurate determination of preference.

Riotte & Peigler (1981) stated *A. senatoria* females could discriminate between *Quercus* species. The number of *A. senatoria* egg masses per *Quercus* species were not significantly different in 1990 and 1991 with a mean of 0.3±0.06 and 0.3±0.04 egg masses per species, respectively (Table 6). In both 1990 and 1991, more oviposition occurred on *Q. palustris* than any other *Quercus* species, and the least number of egg masses were oviposited on *Q. alba*. Hitchcock (1961b) reported *A. senatoria* preferred to oviposit on *Q. velutina* rather than *Q. alba*. *Quercus velutina* was not evaluated in this study. In 1990, the numbers of eggs per *A. senatoria* egg mass was not significantly different and highly variable between *Quercus* species with a mean of 71.4±13.3 eggs per mass. The highest number of eggs per mass was found on *Q. bicolor* and *Q. palustris* with 156.2±67.1 and 152.0±60.7 eggs, respectively. The ratio of females released in 1990 to available *Quercus* species was approximately 1:1. Significant differences in oviposition between *Quercus* species was not detected because a low number of female moths was released.

Moths were collected from lawns in 1990 that had been planted with *Q. palustris* or *Q. phellos*. These two species were the dominant oaks in the area, and larvae undoubtedly fed on them before pupating. Induced preference occurs in insects when larvae develop on a particular host plant and the adults preferentially select to oviposit on the same host plant

(Matthews & Matthews 1978). Induced preference may have been a factor in oviposition on *Q. palustris* and *Q. phellos*.

Quercus preference by *A. senatoria* varied between the southern and northern regions of the United States, and the prevalence of certain species grown in these regions. Riotte & Peigler (1981) reported *Anisota* species preferred *Q. nigra* and *Q. falcata* in the southeastern United States, from North Carolina to Florida to east Texas. Preferred hosts also included *Q. phellos* and *Q. palustris*, while *Q. alba* was infrequently attacked. In southern Florida and western Texas, *Q. virginiana* (Mill.) (live oak), and *Q. stellata* (Wangenh.) (post oak), were not only the primary hosts but also the most prevalent (Riotte & Peigler 1981). In the northern United States, Lintner (1889) reported *Q. alba* trees were not defoliated in Pennsylvania and that *Q. velutina*, *Q. coccinea*, and *Q. ilicifolia* were preferred. Lugger (1890) reported from Minnesota that *Q. alba*, *Q. coccinea*, and *Q. ilicifolia* were heavily defoliated in some years. Herrick (1935) reported a preference for *Q. alba* and *Q. ilicifolia* in New York. Felt (1905, 1926) reported *Q. ilicifolia* was commonly defoliated in New York and the northeastern United States.

All of the 11 *Quercus* species evaluated for *A. senatoria* preference in this study are found in southeastern VA (Dirr 1983) and planted in the urban landscape. Factors used to evaluate preference in this study provided data on *Quercus*

species susceptibility to *A. senatoria* attack. Preferred hosts from the greatest to the least were determined for *Quercus* species grown in southeastern VA. Survival, rate of development, and oviposition of *A. senatoria* were greatest in *Quercus palustris* (pin oak), *Q. coccinea* (scarlet oak), *Q. phellos* (willow oak), and *Q. acutissima* (sawtooth oak); intermediate in *Q. rubra borealis* (northern red oak), *Q. bicolor* (swamp white oak), *Q. prinus* (chestnut oak), *Q. falcata* (southern red), *Q. macrocarpa* (bur oak), and *Q. nigra* (water oak); and poorest in *Q. alba* (white oak).

Solomon (1988) suggested that an abundance of favored host species that produce the most fecund adults is a major cause of pest population increases. *Quercus palustris* and *Q. phellos* were among the most preferred species in this study. These two species are commonly planted in southeastern VA and are heavily defoliated (Coffelt & Schultz 1990b, 1991a). Abundance of preferred *Quercus* species in southeastern VA has contributed to high *A. senatoria* populations. Planting less preferred species in the urban landscape, like *Q. alba*, may help to reduce *A. senatoria* populations.

Table 1. Mean *Quercus* foliage consumption per larva, 1987 field experiments.

		Mean foliage consumed cm^2/larva					
Quercus sp.	N[x]	Early[y]	%[z]	Late	%	Fifth	%
Q. coccinea	2	25.1	0.6	419.3	9.8	3809.1	89.6
Q. palustris	2	61.9	3.0	383.0	19.0	1617.1	78.0
Q. macrocarpa	2	43.9	3.0	245.7	15.0	1333.8	82.0
Mean	2	43.6	1.6	349.3	13.2	2253.3	85.1

[x] N=number of trees.
[y] Early: first-third instars, Late: primarily fourth, Fifth: all fifth instars.
[z] Percent of the total foliage consumed.

Table 2. Mean defoliation and survival of *A. senatoria* on *Quercus* species, 1989 field experiments.

Quercus sp.	Mean±SEM percent[u] Defoliation	N[v]	Survival[w]	N
Q. coccinea	89.5± 5.2 a	10	81.7±12.1[y]	4
Q. rubra[z]	88.0± 8.3 a	10	59.9±11.9	5
Q. palustris	84.4± 9.7 a	9	71.4±15.3	4
Q. phellos	81.2±11.9 ab	4	74.6± 5.6	3
Q. alba	68.7±12.8 abc	8	68.5±13.0	6
Q. falcata	65.0±13.8 abc	5	67.4±18.0	5
Q. bicolor	54.0±12.5 abc	10	67.6±10.3	7
Q. prinus	43.7±11.9 bc	10	59.3± 8.6	8
Q. acutissima	35.5± 9.1 c	9	82.5± 4.7	9
Q. macrocarpa	35.5±11.0 c	9	65.6± 8.9	8

[u] Arcsin transformation performed on percent survival data.
[v] Number of tree replicates.
[w] Percent of larvae that survived to the fourth and fifth instar.
[x] Means followed by the same letter are not significantly different (P>0.05) Waller-Duncan *k* ratio procedure (SAS Institute 1985).
[y] Means were nonsignificant (P>0.05).
[z] *Q. rubra borealis*.

Table 3. Laboratory development of *A. senatoria* reared on *Quercus* species, 1990.

Quercus sp.	Mean±SEM days in each instar									
	First	Nw	Second		Third		Fourth		Fifth		Prepupae	
Q. nigra	9.1±0.2	ax 5	9.5±0.5	a	7.9±0.3	a	7.2±0.3	ab	7.4±0.5	a	3.2±0.1	a
Q. prinus	9.0±0.3	a 4	8.5±0.2	abc	6.6±0.1	cd	6.7±0.4	ab	6.8±0.4	ab	3.3±0.1	a
Q. alba	8.9±0.1	a 5	9.0±0.3	ab	7.3±0.2	abc	7.5±0.2	ab	7.4±0.2	a	3.3±0.1	a
Q. rubra z	8.7±0.1	ab 5	8.3±0.3	abc	7.0±0.2	abc	6.8±0.3	ab	7.0±0.5	ab	3.6±0.2	a
Q. falcata	8.7±0.2	ab 5	8.0±0.3	bcd	6.3±0.1	cd	6.5±0.2	ab	5.3±0.4	bc	3.6±0.1	a
Q. bicolor	8.6±0.2	ab 5	8.6±0.5	abc	6.8±0.3	a-d	6.5±0.2	ab	6.2±0.4	abc	3.5±0.2	a
Q. macrocarpa	8.6±0.3	ab 4	7.3±0.2	cd	6.3±0.1	cd	8.0±2.0	a	5.0±0.0	c	3.5±0.4	a
Q. coccinea	8.6±0.1	ab 5	7.5±0.0	cd	7.0±0.2	abc	6.3±0.2	b	6.5±0.1	ab	3.4±0.2	a
Q. palustris	8.3±0.1	ab 5	6.8±0.1	d	5.9±0.3	d	6.2±0.1	b	6.6±0.1	ab	3.7±0.1	a
Q. acutissima	8.3±0.2	ab 5	8.3±0.2	abc	7.3±0.2	abc	6.8±0.2	ab	6.8±0.2	ab	4.1±0.4	a
Q. phellos	7.7±0.3	b 5	7.7±0.2	bcd	7.5±0.1	ab	7.6±0.1	ab	6.8±0.2	ab	3.6±0.2	a

w Number of replications were the same for each instar.
x Means followed by the same letter are not significantly different (P>0.05) Waller-Duncan *k* ratio procedure (SAS Institute 1985).
z *Q. rubra borealis*.

Table 4. Survival and pupal weight of *A. senatoria* reared on *Quercus* species, 1990.

Quercus sp.	Percent Survival[v]		N[w]	Mean±SEM Pupal weight (g) Female	N	Male	N
Q. nigra	48.0± 8.0	cd[x]	5	0.8±0.05 ab	5	0.5±0.01[y]	3
Q. prinus	64.0±18.3	a-d	4	0.8±0.03 ab	2	0.5±0.06	2
Q. alba	88.0± 8.0	ab	5	0.9±0.10 ab	3	0.5±0.01	4
Q. rubra[z]	88.0± 8.0	ab	5	1.0±0.05 a	5	0.5±0.04	4
Q. falcata	44.0±19.4	cd	5	0.6±0.02 b	2	0.4±0.03	3
Q. bicolor	70.0±13.0	a-d	5	0.9±0.04 ab	3	0.5±0.03	3
Q. macrocarpa	32.0±20.6	d	4	no pupae		0.6±0.09	2
Q. coccinea	96.0± 4.0	a	5	1.0±0.08 a	5	0.5±0.02	5
Q. palustris	84.0± 7.4	abc	5	1.0±0.04 a	5	0.4±0.01	5
Q. acutissima	92.0± 4.8	ab	5	1.0±0.03 a	2	0.5±0.08	3
Q. phellos	84.0±16.0	abc	5	0.8±0.03 ab	3	0.4±0.03	5

[v] Arcsin transformation performed on percent survival data.
[w] N=number of replications.
[x] Means followed by the same letter are not significantly different (P>0.05) Waller-Duncan *k* ratio procedure (SAS Institute 1985).
[y] Means were nonsignificant (P>0.05).
[z] *Q. rubra borealis*.

Table 5. Larval preference of first and second instar *A. senatoria* for *Quercus* species, 1990 laboratory experiments.

Quercus sp.	Mean±SEM leaf disks consumed (mm^2) First instar	Second instar
Q. alba	84.7±47.5[y]	133.7±37.9
Q. falcata	38.8±13.1	106.6±54.1
Q. coccinea	30.8±15.0	158.5±64.4
Q. bicolor	25.8±15.0	15.3±10.2
Q. nigra	24.2±14.2	161.1±34.9
Q. phellos	23.5±12.2	65.1±31.2
Q. palustris	22.2±22.2	153.7±64.8
Q. acutissima	11.5± 7.9	46.6±33.0
Q. prinus	4.0± 4.0	76.7±45.5
Q. rubra[z]	0.0± 0.0	141.2±33.6
Q. macrocarpa	0.0± 0.0	33.6±33.6

[y] Means were not significantly different (P>0.05).
[z] *Q. rubra borealis*.
There were eight replications of each species for first and second instars.

Table 6. Ovipositional preference of *A. senatoria* for *Quercus* species, 1990-1991 field experiments.

Quercus sp.	Mean±SEM 1990 No. masses per sp.	N[x]	Mean±SEM 1991 No. masses per sp.	N	Mean±SEM 1990 No. eggs per mass	N
Q. palustris	0.8±0.3[y]	12	0.5±0.1	12	152.0±60.7	12
Q. falcata	0.5±0.4	7	0.4±0.2	7	74.4±48.0	7
Q. acutissima	0.5±0.3	10	0.1±0.1	10	78.9±44.5	10
Q. bicolor	0.5±0.2	14	0.4±0.2	14	156.2±67.1	14
Q. rubra[z]	0.5±0.1	16	0.2±0.1	16	89.3±31.4	16
Q. coccinea	0.4±0.2	11	0.3±0.1	11	67.3±45.2	11
Q. phellos	0.3±0.2	9	0.2±0.1	9	49.1±33.4	9
Q. macrocarpa	0.2±0.1	14	0.4±0.1	14	69.8±40.6	14
Q. prinus	0.1±0.1	12	0.3±0.2	12	7.2± 7.2	12
Q. alba	0.0±0.0	13	0.1±0.1	13	0.0± 0.0	13
Q. nigra	0.0±0.0	8	0.3±0.1	8	0.0± 0.0	8
Grand Mean	0.3±0.06	126	0.3±0.04	126	71.4±13.3	126

[x] Number of tree replicates 1990-1991.
[y] Means were not significantly different (P>0.05).
[z] *Q. rubra borealis*.

Chapter 10

Development of an aesthetic injury level to decrease pesticide use against orangestriped oakworm (Lepidoptera: Saturniidae) in an urban pest management project

Introduction

The concept of integrated pest management (IPM) had its beginnings in agroecosystems, where it was first proposed and used successfully in several cropping systems (Stern et al. 1959, Metcalf & Luckmann 1975). Urban landscape IPM has evolved over the years from this basic framework and has found limited practice in arboriculture today (Nielsen 1989). Previous investigations have resulted in the development and implementation of urban IPM projects in California (Olkowski 1974), Maryland (Holmes & Davidson 1984, Raupp & Noland 1984, Reardon et al. 1987) and Virginia (Ticehurst & Finley 1988). Some commercial arborists have established IPM programs through a national plant health care program (Funk 1988).

As in the agroecosystem, successful IPM programs include scouting to determine pest life stage and abundance so that rational control decisions can be made (Raupp 1985, Ball 1987). Intervention tactics in urban landscape management are based on aesthetics and aesthetic injury levels (AIL), rather than economic injury levels as in agriculture. The major impediment to developing urban IPM programs has been a lack of accurate decision-making guidelines for pests causing aesthetic damage (Potter 1986, Raupp et al. 1988).

Approximately 200,000 *Quercus* (oak) species have been planted on municipal streets and parks in Norfolk, VA over the last 50 years. Tree management is the responsibility of the

Bureau of Parks and Forestry (BPF). Severe defoliation of Norfolk trees by *Anisota senatoria* (J. E. Smith) (Lepidoptera: Saturniidae), the orangestriped oakoworm, has occurred since 1981, and complaints to the BPF and elected officials have increased. Over 60% of the complaints have been for frass and larvae on walkways, and 35% for defoliation and tree mortality (Chapter 12). Localized pesticide applications for *A. senatoria* control and other pests are applied at citizen request. Although not uncommon, this policy is not cost effective, and adds significant pesticide load to the urban environment (Coffelt & Schultz 1987). Objectives of this study were to determine whether a monitoring program coupled with an AIL could be used to manage *A. senatoria* with minimal pesticide inputs.

Materials and Methods

A value assessment was conducted to determine the economic and aesthetic benefits of the primary *Quercus* species planted in Norfolk, VA. Pesticide use and program costs were quantified before and after program implementation. Establishment of an AIL and monitoring procedure was an integral part of the program. Analysis of the pest management program was evaluated by citizen requests and defoliation records.

Value Assessment. One residential Norfolk area of approximately 40.5 ha was selected to determine the economic

value of the municipal street trees. The area contained approximately 450 *Q. palustris* Muench., pin oaks, and 50 *Q. phellos* L., willow oaks. Infestations of *A. senatoria* in Norfolk were localized and this area was selected because of its history of defoliation. *Quercus palustris* and *Q. phellos* planted on city property between the sidewalk and street were selected. One hundred *Q. palustris* and *Q. phellos* were chosen from the area using a random number generator (SAS Institute 1985). The diameter at breast height (dbh) was measured, and the International Society of Arboriculture formula was used to calculate the mean dollar value per tree (Neely 1983). This formula included an aesthetic factor (tree condition), and value assessment was determined to quantify the benefits of urban oaks.

Pesticide Use Patterns and Program Costs. Pesticide use and costs were determined from Norfolk records of *A. senatoria* treatment (1981-1988) for the entire city. Pesticide volume (formulated material), number of citizen requests for pesticide application, sites with trees that were treated and had repeated applications (work orders), and number of trees treated were tabulated. Costs were converted to real costs by adjusting for inflation using the consumer price index (Bureau of Labor Statistics 1988). Real costs were calculated according to the method of Leuschner (1984). Total real

costs, including labor and pesticides, were computed for each year. These total costs included scouting in 1988.

AIL and Monitoring. The AIL was determined from a citizen survey (Chapter 12) conducted in June and October of 1988, and from the effects of different levels of defoliation on tree vigor as measured by root starch content (Chapter 6). Citizens were surveyed (n=132) in two Norfolk subdivisions that had experienced widespread *A. senatoria* defoliation. Citizens were shown photographs of five defoliation levels (15, 25, 50, 75, 100%) and were asked what level of damage they were willing to accept (0% was provided verbally as a choice). Survey questions were pre-tested in June and slight adjustments in format were made to increase clarity. The full survey was conducted in October of 1988. To determine the effect of defoliation on starch content, two primary roots were randomly selected from each *Q. palustris*. Trees that received 0% (n=7), 25% (n=3), and 100% (n=7) defoliation in August were sampled in December of 1988. Roots were washed, debarked, dried at 70°C, and ground with a Cyclotec mill (Model 1093, Tecator, Hoganas, Sweden) to yield 200 mg of tissue for analysis. Total nonstructural carbohydrates (TNC) were enzymatically hydrolyzed (Smith 1969), total free sugars (TFS) were determined using an automated procedure (Davis 1976), and starch levels were determined (TNC-TFS).

Percentage starch (dry weight) and arcsin transformed values were subjected to analysis of variance (ANOVA), and means were separated by the Waller-Duncan *k* ratio procedure (*k* ratio=100) (SAS Institute 1985).

Anisota senatoria populations were monitored daily on 10% of the *Quercus* species in four residential areas of the city during peak larval periods (late July and August) by recording life stages and abundance from intact 30 cm branch segments. Defoliation estimates were made by visually dividing trees into four quadrants with each quadrant corresponding to 25% of the total leaf area. The percentage leaf area missing in each quadrant was visually estimated (to the nearest 5%). The cumulative defoliation from the four quadrants was recorded. Monitoring data showed where defoliation was approaching damaging levels, the BPF was notified the same day of these locations, and pesticide applications were scheduled.

Citizen Requests and Defoliation. Records of citizen requests for spraying were analyzed to determine the feasibility of basing a spray program on citizen complaints. The number of citizen requests for pesticide application and corresponding defoliation estimates (as previously described) were evaluated in 1987 and 1988. Addresses of citizens who called the BPF requesting pesticide treatment for *A. senatoria* were obtained during August and September of both years. Site visits were made after each request on the same or following

day. All *Quercus* species on city property in front of the residence were observed and defoliation estimated. Effectiveness of the spray decisions was determined by comparing the total number of 90-100% defoliated trees from late August to early September during the year of the program (1988) with that observed in previous years (1986-1987).

Results and Discussion

Value Assessment. *Quercus palustris* and *Q. phellos* with a dbh of 51.5±1.2 cm had a mean economic and aesthetic value (±SEM) of $5,131±237.8. Aesthetic benefits of urban shade trees also include the physical health and psychological well-being of residents (Starkey 1979, Potter 1986). Urban trees increase real estate values as much as 15-20% (Payne et al. 1973, Anonymous 1988), and moderate ambient temperature (Federer 1976). Economic and aesthetic benefits of urban trees justify development of sound pest management strategies.

Pesticide Use Patterns and Program Costs. Pesticide spraying for *A. senatoria* increased for six consecutive years, reaching a peak in 1986 (Table 1). Pesticide volume (formulated material) rose from 2,650 liters in 1981 to a peak of 55,172 liters in 1986, and decreased slightly in 1987. Pesticide treatments (1981-1987) were applied for *A. senatoria* infestations at citizen request for trees facing their property. Requests peaked at 130 in 1985. Treatment practices were modified in 1986 and all trees on an entire

city block were treated upon citizen complaint originating from that block. This policy change was implemented to decrease complaints; however, despite this policy, complaints remained high (Table 1). *Anisota senatoria* spread throughout the city from 1981-1986, as shown by the increased number of trees that were treated at sites (6-89). Work orders increased and represented the number of trees that were treated at sites plus up to four repeated applications. Trees that were treated increased from 70 in 1981 to 1,287 in 1986. In 1987, a preventive spray program was implemented and city trees within areas that had a history of *A. senatoria* infestations were treated. This strategy decreased the number of requests, but spray volume and the number of trees that were treated remained high (Table 1). In addition, BPF employees treated some infested city trees upon request.

Pesticide use patterns did not indicate *A. senatoria* population trends because pesticides were applied at citizen request and not according to population densities. In 1988, *A. senatoria* populations exceeded prior levels in one Norfolk subdivision, and were equal to 1986 levels in another, according to BPF officials. Population levels appeared to be constant or increasing from 1986-1988.

Pesticide and labor costs for 1981-1987 were based on a mean 1985 price and hourly wage. Total real costs (pesticides plus labor) for *A. senatoria* control rose sharply from 1981-

1986, peaking at $6,795 (Table 2). Total real costs decreased in 1987, as lower volume and less expensive pesticides were used. These costs represent a substantial expense to the city. Pesticides applied included malathion, diazinon, carbaryl, and acephate.

AIL and Monitoring. Results from the surveys used to measure acceptable levels of defoliation were similar for June and October, and only the October results are shown (Table 3). Survey data showed 70% of the respondents were willing to tolerate some defoliation. Equal citizen responses were given between acceptance of 0, 15, and 25% damage; 28% of the citizens thought that 25% defoliation was aesthetically acceptable. In addition to the aesthetic component of the AIL, the effect of defoliation on root starch reserves was examined. Root starch reserves of deciduous trees have been shown to be indicators of tree vigor (Wargo et al. 1972, Carroll et al. 1983). Staley (1965) and Parker & Houston (1971) showed defoliation decreased root starch reserves. There were significant differences ($P<0.05$) in percent starch content (dry weight) for defoliated trees. Trees that were 100% defoliated had a significantly lower mean starch content (2.9%) than undefoliated trees (6.6%) ($P<0.05$), but trees that were 25% defoliated did not differ significantly in mean starch content (4.8%) from undefoliated trees ($P>0.05$). These data indicated that 25% defoliation would not affect tree

vigor. Because *A. senatoria* defoliates in August and September, it has less physiological impact on tree vigor as compared with an early season defoliator such as the gypsy moth, *Lymantria dispar* (L.) (Lepidoptera: Lymantriidae) (Wargo 1981). Based on aesthetic considerations and data that showed 25% defoliation did not measurably affect tree vigor, an AIL of 25% damage was used to determine if pesticide applications were justified. In 1988, recommendations were made to the BPF to spray only trees that had more than 25% damage at the time of monitoring. Monitoring data were forwarded daily to the BPF to minimize additional defoliation if treatment was required.

Monitoring and use of a 25% AIL resulted in an 80.3% decrease in pesticide use compared with 1987 (Table 1). The number of *Quercus* species receiving treatment decreased dramatically. Trees that were treated at sites and work orders were nearly identical in 1988, which indicated few trees at sites were re-treated. Total real costs for pesticides, labor, and monitoring in 1988 were $1,566, a 55% cost reduction compared with 1987 (Table 2). Diazinon and acephate were the pesticides used. Monitoring costs were high ($877) because trees in the IPM program were scouted daily and defoliation assessed continuously for the 25% AIL. Smith and Raupp (1986) reported that scouting costs were high in their IPM program due to regular monitoring.

The use of 25% defoliation as an AIL will allow city employees to monitor *Quercus* species and decide if treatment is necessary by assessing defoliation levels. Raupp et al. (1988) suggested that aesthetic considerations alone may be valuable in decision-making for pests causing aesthetic injury, and Potter (1986) stated an AIL can be used as a basis for management decisions. In urban landscape management, AIL and thresholds are low and may be similar because public perception is usually intolerant of accepting slight damage. Raupp et al. (1988) found that a difference of only three first-instar bagworms, *Thyridopteryx ephemeraeformis* (Haworth) (Lepidoptera: Psychidae), separated the threshold from the AIL. Establishment of a 25% AIL provided a practical decision-making tool for monitoring programs. The relationship between perceived damage and true injury to ornamental plants is needed in landscape pest management (Raupp et al. 1988). Citizens were willing to accept up to 25% damage (Table 3), a level that did not significantly reduce tree vigor. This approach of quantifying an aesthetic and biological indicator to establish decision-making injury levels could be applied to other pests in the ornamental landscape.

Citizen Requests and Defoliation. Requests for *A. senatoria* treatment occurred from August 1 to September 13 in 1987-1988. Evaluation of citizen requests indicated needless

pesticide applications were made primarily for two reasons. First, citizens requested treatment when defoliation was negligible. In 1987, 70% of requests were for trees with 1-5% defoliation (Table 4), and these trees were treated because an AIL had not been implemented. Some citizen requests for trees with 1-5% defoliation were not treated (n=14) in 1987 because trees were on private grounds or were used for ecological *A. senatoria* studies. These trees did not reach 25% defoliation at the end of the season (Mean = 9.5%). Based on these data, the majority of trees with 1-5% defoliation (Table 4) would not have exceeded the 25% AIL. A significant pesticide reduction (84%) would have occurred in 1987 if a 25% AIL had been implemented. These data indicate there was less citizen concern about defoliation and more concern about the nuisance caused by frass and larvae on walkways. Second, treatment requests in September were received too late to mitigate the effect of *A. senatoria*. Trees that received 90-100% defoliation in September 1987-1988 were treated by the BPF. Late citizen requests (90-100% defoliation) in 1987-1988 comprised 11.1 and 12.0% of all requests, respectively (Table 4). Treatment at this time is ineffective because fifth instars are less susceptible to pesticides, and are migrating from the trees to pupate.

Defoliation of 100% causes refoliation which has the greatest adverse effect on tree physiology and growth (Wargo

1981). A survey of 90-100% defoliated trees was conducted from 1986-1988 in four Norfolk subdivisions (Mean = 38 ha) (Table 5). Even with heavy pesticide use in 1986, 39 city trees (2.8%) were 90-100% defoliated. In 1987, 34 city trees (2.4%) were 90-100% defoliated. A slight increase (1.0%) in 90-100% defoliated trees occurred in 1988. Officials from the BPF stated *A. senatoria* populations were the highest in eight years at Area 2. This localized increase in *A. senatoria* probably accounted for the slight increase in defoliation in 1988.

Despite the success with *A. senatoria* pest management, improvements could be made. Requests for control increased from 63 in 1987 to 104 in 1988 (Table 1) because citizens had been accustomed to the BPF spraying all trees on demand. During the monitoring program, citizens who asked were informed about *A. senatoria* biology and the benefits of reducing pesticide use by developing an AIL. The majority of citizens were receptive to the program. Repeated requests (12) in 1988 were from irate citizens demanding pesticide application despite defoliation below 25%. These individuals were against the program, indicating an AIL will not be received equally by all citizens. Zungoli and Robinson (1984) discussed problems establishing an AIL and benefits of educational programs to enhance acceptance of an AIL.

Anisota senatoria has become a serious problem on oaks in the city of Norfolk. The economic value and aesthetic benefits of urban oaks and the large pesticide volume used in the urban environment justify the development of control program based on monitoring and use of an AIL. Basing control decisions on estimates of defoliation reduced pesticide use without an attendant increase in defoliation.

Table 1. Pesticide suppression against *A. senatoria* before and after IPM was implemented, Norfolk, VA, 1981-1988.

Year	No. liters sprayed	No. citizen requests	No. sites treated	No. work orders	No. trees treated
		Before AIL implementation			
1981	2,650	20	6	6	70
1982	2,801	20	8	11	80
1983	9,217	20	16	17	263
1984	25,362	75	43	51	609
1985	30,681	130	67	117	862
1986	55,172	120	89	118	1,287
1987	39,860	63	59	90	1,239
		After AIL implementation			
1988	7,866	104	21	22	224

Table 2. Real costs ($) associated with *A. senatoria* suppression before and after IPM was implemented, Norfolk, VA, 1981-1988.

Year	Insecti-cides	Labor	Monitoring	Total($)
		Before AIL implementation		
1981	51	208		259
1982	92	220		312
1983	308	695		1,003
1984	884	1,831		2,715
1985	744	2,157		2,901
1986	2,953	3,842		6,795
1987	830	2,712		3,542
		After AIL implementation		
1988	$177	$512	$877	$1,566

Table 3. Citizen response to the question "How much *Quercus* damage by *A. senatoria* would you be willing to accept?", Norfolk, VA, 1988.

% Damage willing to accept	% Responding		Mean
	Area 1[a]	Area 2[b]	
0	30	30	30
15	33	30	31.5
25	28	28	28
50	4	12	8
75	1	0	0.5
>76	4	0	2

[a] n=82 citizens.
[b] n=50 citizens.

Table 4. Number (%) of citizen requests for *A. senatoria* treatment and associated defoliation levels, Norfolk, VA, 1987-1988.

% Defoliation	1987	1988	Total (Mean %)
1-5	44 (70.0)	46 (44.2)	90 (57.1)
6-15	6 (9.5)	24 (23.0)	23 (16.3)
16-25	3 (4.8)	8 (8.0)	11 (6.4)
26-50	2 (3.1)	12 (12.0)	14 (7.6)
51-75	1 (1.5)	1 (0.8)	2 (1.1)
76-89[a]			
90-100	7 (11.1)	12 (12.0)	19 (11.5)

[a] Defoliation not observed.

Table 5. Number (%) of *Quercus* species in four subdivisions of Norfolk, VA, with 90-100% defoliation by *A. senatoria*, 1986-1988.

Subdivisions	Defoliated trees			Total trees	Grand mean
	1986	1987	1988		
1	28 (10.6)	16 (6.1)	27 (10.3)	263	
2	2 (0.8)	8 (3.2)	15 (6.0)	251	
3	9 (1.8)	8 (1.6)	5 (1.0)	498	
4	0 (0.0)	2 (0.5)	0 (0.0)	376	
Totals	39 (2.8)	34 (2.4)	47 (3.4)	1,388	40 (2.8)

Chapter 11

Quantification of an aesthetic injury level and threshold for an orangestriped oakworm urban pest management program

Introduction

One of the foundations of integrated pest management (IPM) is tolerating a given amount of insect damage and developing a decision guideline based on thresholds. Tolerating insect damage was first proposed by Pierce (1934). Pierce suggested insect damage was assessable only when yield was reduced below normal. Stern at al. (1959) later proposed the economic injury level (EIL) and economic threshold (ET). The EIL and ET can be defined as the lowest pest population density that will cause economic damage and the pest population density at which active controls should be applied to prevent pests from reaching the EIL (Stern et al. 1959). With ornamental pests causing aesthetic damage, economic loss may not be involved, impossible to measure, or insignificant in decision-making (Potter 1986). Olkowski (1974) first proposed substituting aesthetic for economic and applied an aesthetic injury level (AIL) in an urban landscape IPM program. Various thresholds have been used in ornamental landscapes including emotional (Evans 1984), decision (Raupp et al. 1988), action (Nielsen 1989), and aesthetic (Raupp et al. 1988).

The lack of decision-making guidelines for aesthetic damage and pests has hindered development of urban landscape IPM programs (Raupp et al. 1988). Some research on establishing an AIL has been conducted. Zungoli & Robinson

(1988) found the AIL varied with the extent of pest infestation. They found that larger infestations of German cockroach, *Blattella germanica* (L.) (Orthoptera: Blattidae), caused a greater tolerance by citizens. Coffelt & Schultz (1990b) found the opposite relationship for infestations of *Anisota senatoria* (J. E. Smith) (Lepidoptera: Saturniidae), orangestriped oakworm. They found that increased damage caused less tolerance by citizens. An AIL based on 25% defoliation was established for *A. senatoria* infestations in the urban landscape (Coffelt & Schultz 1990b). However, the AIL was based on assessing daily defoliation levels and was time consuming and labor intensive. A threshold level of *A. senatoria* densities should be established that will complement this AIL.

The objectives of this study were to quantify the relationship between *A. senatoria* densities and defoliation for different sized *Quercus palustris* Muench., pin oak, in the urban landscape.

Materials and Methods

Studies were conducted from July to September, 1987-1990. Seven *Q. palustris* were selected in 1987 and 18 in 1988 from Norfolk, VA sites that had natural infestations of *A. senatoria* egg masses (ranged from 2-18 egg masses per tree). Infested trees were isolated from each other, which decreased the probability of larval migration between trees.

Nineteen *Q. palustris* in 1989 and 49 in 1990, located in Norfolk, Virginia Beach, and Chesapeake, VA were artificially infested with *A. senatoria* egg masses. Egg masses within 1-2 days of eclosion were collected from infested *Q. palustris*. Leaf sections containing egg masses were pinned on leaf undersides of the selected trees. Egg masses were examined daily for egg hatch (1989-1990). If an egg mass had desiccated, then a fresh egg mass was substituted. Thirteen subsamples of egg masses from 1987-1990 were randomly selected and the number of eggs per egg mass counted and the percent egg eclosion calculated.

Diameter at breast height (dbh) was measured and height visually estimated for the trees in this study. Treatments were the number of *A. senatoria* egg masses that naturally occurred (1987-1988) or were artificially attached to trees (1989-1990). Trees that had a dbh within the range of 8.9-13.7 cm (mean of 12.6 cm) received 1, 2, 3, 4, 8, and 12 egg masses per tree among 19 trees. The number of egg masses per tree among 32 trees was 2, 3, 4, 5, 6, 7, 9, 10, 13, 14, and 15 for trees that had a dbh within the range of 14.0-27.6 cm (mean of 19.1 cm). Trees that had a dbh within the range of 23.0-30.0 cm (mean of 26.4 cm) received 2, 3, 4, 5, 6, 8, 10, and 16 egg masses per tree among 30 trees. The number of egg masses per tree among 12 trees was 10, 15, 18, and 20 for trees that had a dbh within the range of 31.0-40.4 cm (mean of

35.0 cm). Trees planted in close proximity had trunks wrapped with tape, covered with petroleum jelly, to prevent *A. senatoria* migration (unpublished data). Trees were checked every 2 weeks to ensure that larvae were alive and pesticides were not applied. Tape was removed from trees in early September. Defoliation was assessed in mid-September of all 4 years when larvae had migrated from trees.

Data were subjected to analysis of variance (ANOVA) and simple linear regression (PROC REG) (SAS Institute 1985).

Results and Discussion

The mean (±SEM) number of eggs per egg mass was 419.0±11.1. The mean egg hatch was 96.8±0.3% (n=52). The number of egg masses that caused a given amount of defoliation was not significantly different ($P>0.05$) between years, so data were combined (1987-1990). There was a significant ($P<0.05$) linear relationship between the number of egg masses and defoliation in all tree categories (Figures 1-4). Coefficients of determination were high for all tree categories and the highest r^2 was for trees with a mean dbh of 26.4 cm (Figure 3). The lowest r^2 was for trees with a mean dbh of 35.0 cm (Figure 4).

Based on the regression equations given in Figures 1-4, the number of egg masses that caused 25 and 100% defoliation of *Q. palustris* ranged from approximately one to nine and four

to 28, respectively (Table 1). First and second instar *A. senatoria* remained in their gregarious groups (Chapter 2). Therefore, the number of egg masses can be extrapolated to include the number of first and second instars. For example, if a tree was within the dbh and height range of 8.9-13.7 cm and 3.6-5.8 m, and had four or more egg masses of first and second instar groups, then data (Figure 1) would predict 100% defoliation.

Thresholds (Table 1) were established for *Q. palustris*, a preferred host of *A. senatoria* in southeastern VA (Chapter 9). The relationship between egg mass density and defoliation may differ with *Quercus* species. Thresholds should be established for each *Quercus* species attacked by *A. senatoria*. Olkowski et al. (1978) found an AIL for *Phryganidia california* (Packard) (Lepidoptera: Dioptidae), California oakworm, was higher on *Q. agrifolia* Nee, California live oak, than *Q. ilex* L., holly oak.

These data (Figures 1-4, Table 1) have important implications in an urban IPM program for *A. senatoria*. Previous research showed an AIL of 25% damage (Coffelt & Schultz 1990b) significantly reduced pesticide usage without an attendant increase in defoliation, but *A. senatoria* densities were not reported. Scouting for 25% damage required daily monitoring and amount of defoliation changed daily. Changes in defoliation did not allow adequate time to

implement IPM control strategies. In this study, the relationship between a threshold and AIL was quantified. Thresholds that were based on densities of *A. senatoria* egg masses predicted the 25% AIL. These data will allow for prediction of percent defoliation when monitoring *Q. palustris* for *A. senatoria* egg masses. Establishment of these thresholds will complement the 25% AIL and provide a better decision-making guideline.

Researchers have often resorted to selecting an AIL without a threshold when implementing IPM programs. Olkowski et al. (1978) set an AIL of 10 *P. california* larvae per 25 shoots because this density caused unsightly damage. This level was not based on population data correlated to damage levels (Olkowski et al. 1978) and a threshold was never utilized. However, this AIL was successful in eliminating 45% of *Quercus* species from pesticide treatments. Zungoli & Robinson (1984) discussed establishing an AIL for *B. germanica* but threshold levels were not mentioned.

In urban landscape management, AIL and thresholds are low and may be similar because public perception is usually intolerant of much damage (Coffelt & Schultz 1990b). The ET is usually set below the EIL in agronomic crops to allow time to respond and take appropriate action (Pedigo 1989). Raupp et al. (1988) determined an AIL based on when nursery customers perceived damage and a threshold when they initiated

control. They found a threshold of nine first instar bagworms, *Thyridopteryx ephemeraeformis* (Haworth) (Lepidoptera: Psychidae), was higher than the AIL of six first instars. Because the threshold was higher than the AIL, implementation and practical usage of these *T. ephemeraeformis* densities is unrealistic. These data (Raupp et al. 1988) indicated the difficulty that can exist in developing injury and threshold levels in ornamental landscapes. Furthermore, Raupp et al. (1988) found injury levels based on the economic market value were similar to injury levels based on aesthetic perceptions from customer surveys.

Low AIL values indicated that the relationship between perceived damage and true injury was lacking in ornamental landscapes (Raupp et al. 1988). Increased tolerance of cosmetic plant injury was desired, especially if plant vigor was not affected over time. Coffelt & Schultz (1990b) quantified the relationship between *Quercus* species defoliation and true injury by conducting root starch analysis.

These data suggest that the AIL in ornamental plants be based on quantifying the amount of injury or defoliation that will cause significant aesthetic damage. The threshold should be based on the pest population density at which active controls should be implemented to prevent significant damage, or the AIL. This can be conducted by monitoring plants, and

as pest densities approach the threshold, control methods are then initiated.

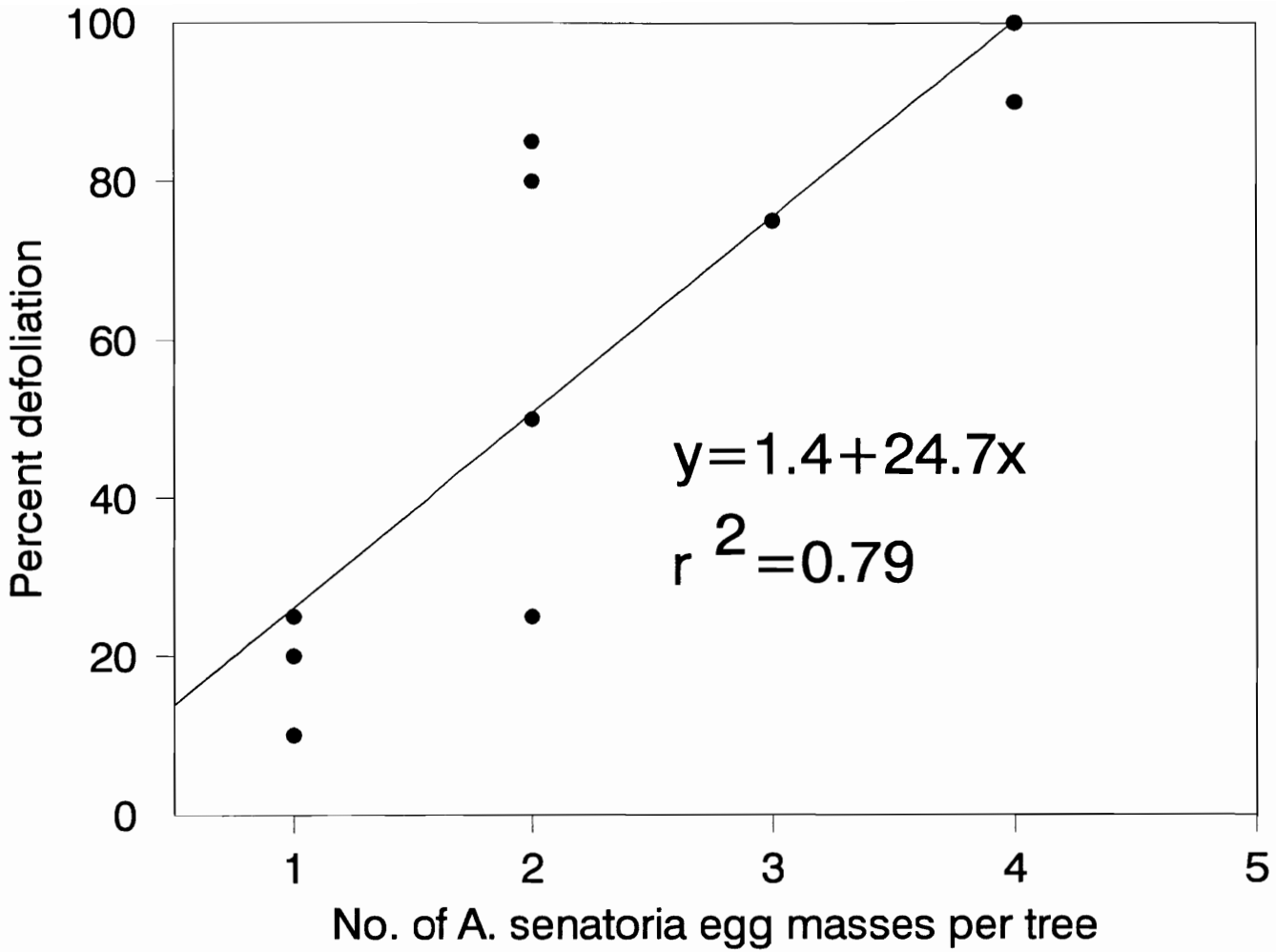

Figure 1. Number of *A. senatoria* egg masses that caused *Q. palustris* defoliation with mean dbh=12.6 cm, height=5.2 m, 1987-1990.

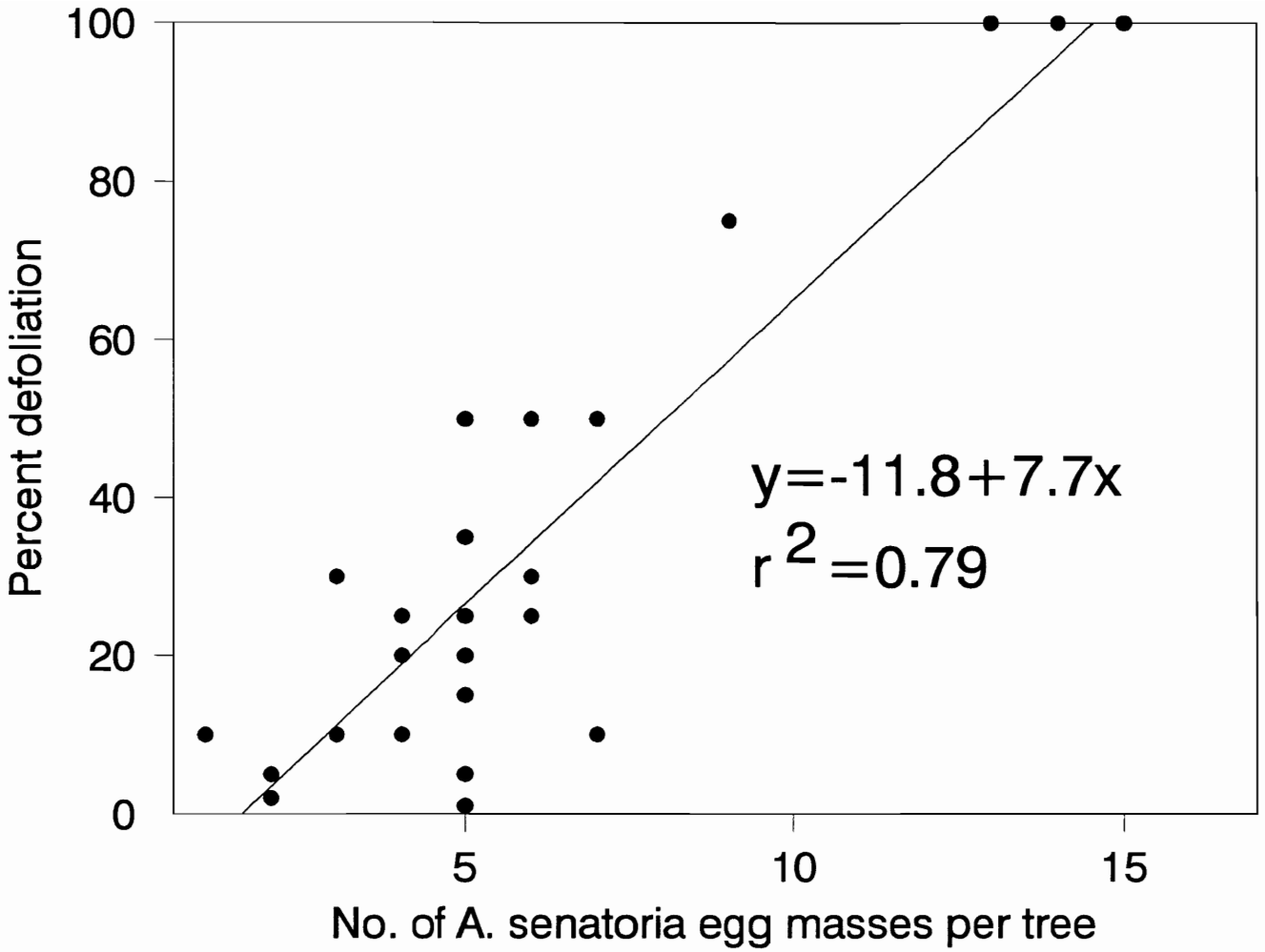

Figure 2. Number of *A. senatoria* egg masses that caused *Q. palustris* defoliation with mean dbh=19.1 cm, height=7.7 m, 1987-1990.

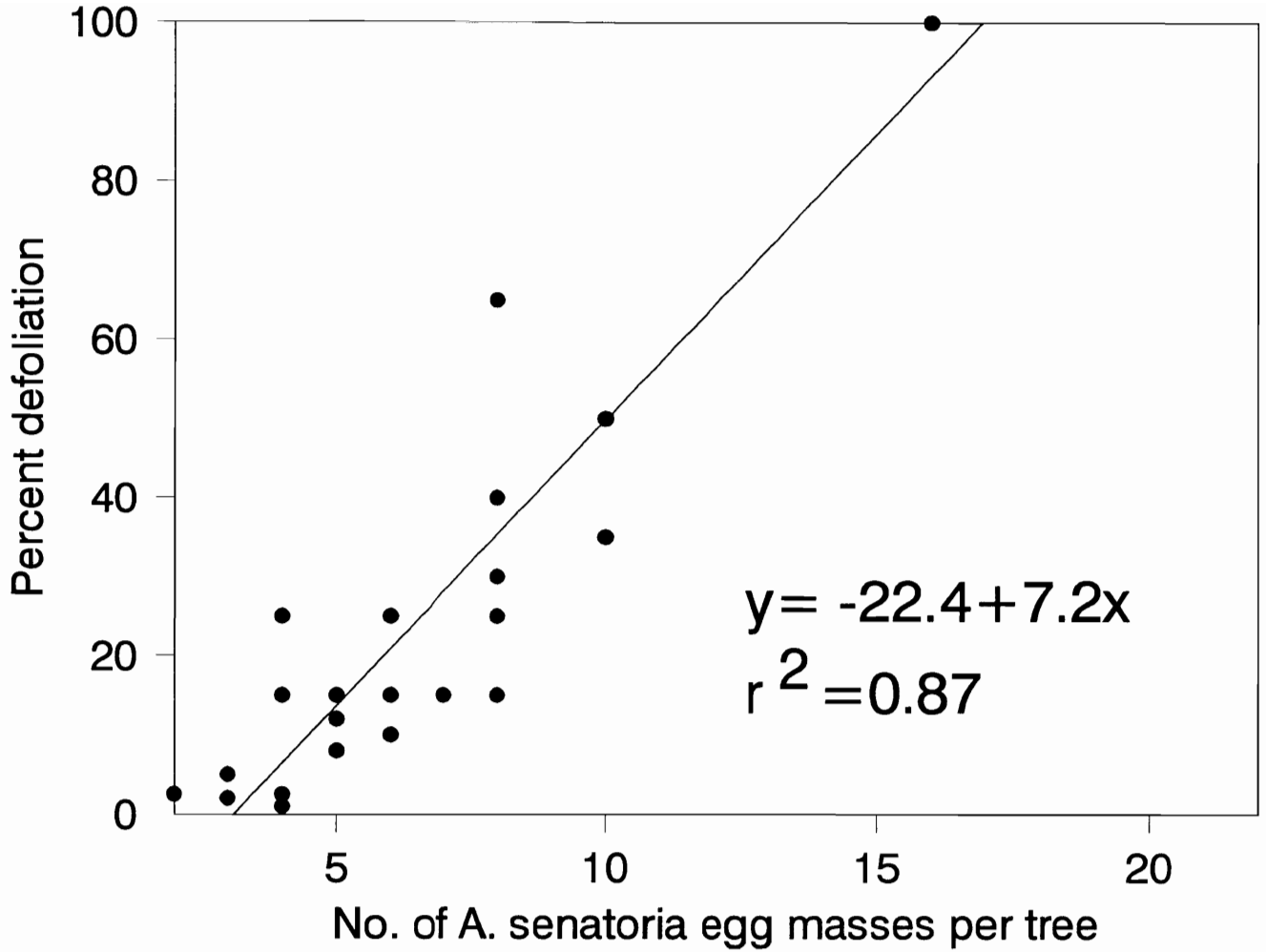

Figure 3. Number of *A. senatoria* egg masses that caused *Q. palustris* defoliation with mean dbh=26.4 cm, height=10.4 m, 1987-1990.

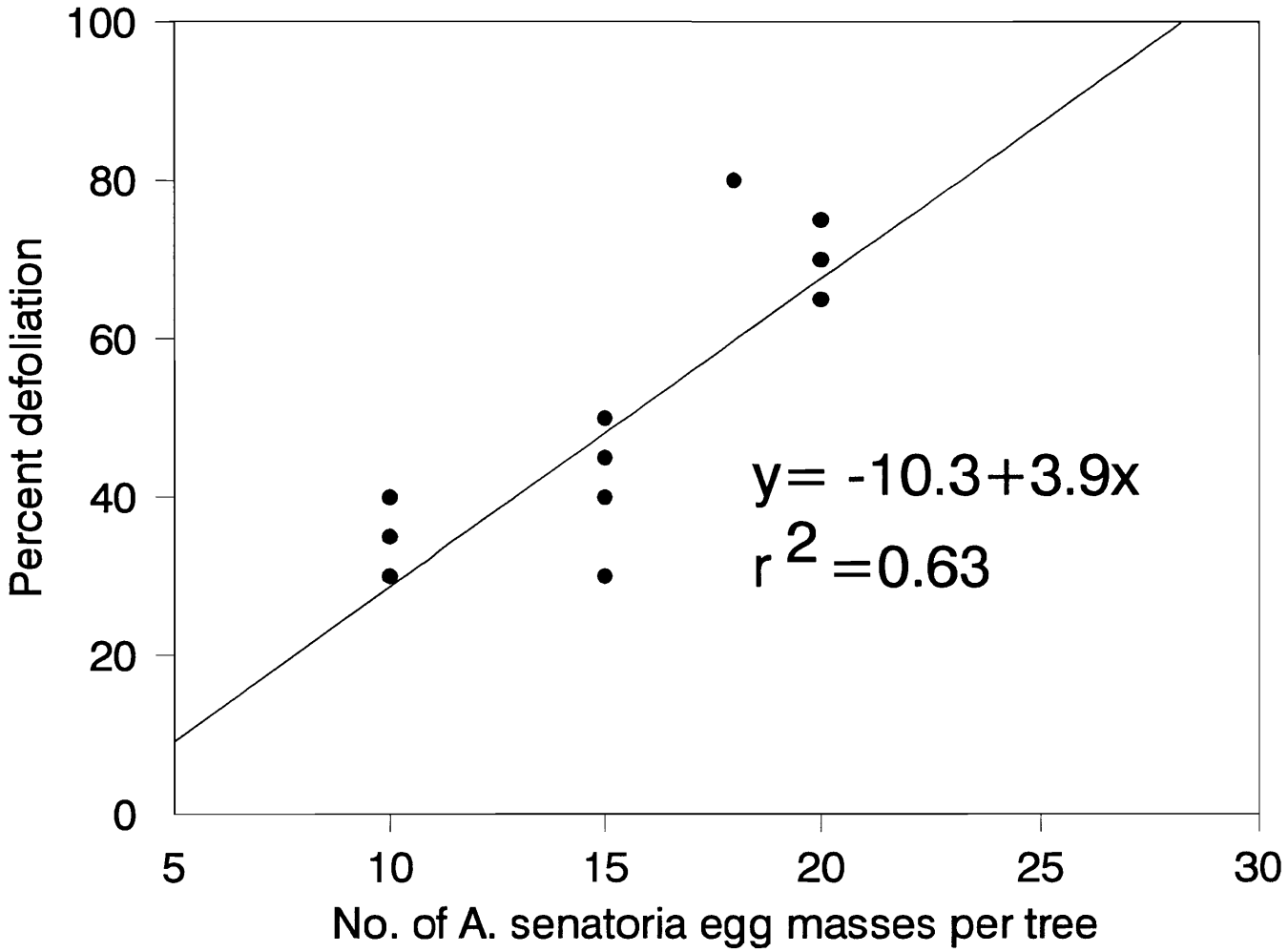

Figure 4. Number of *A. senatoria* egg masses that caused *Q. palustris* defoliation with mean dbh=35.4 cm, height=13.2 m, 1987-1990.

Table 1. Mean diameter and height of *Q. palustris* and number of *A. senatoria* egg masses that caused 25 and 100% defoliation, 1987-1990.

Mean±SEM					No. egg masses that caused % defoliation	
dbh (cm)[y]	N[z]	Range	Height (m)	Range	25 (AIL)	100
12.6±0.3	14	8.9-13.7	5.2±0.1	3.6-5.8	0.9	4.0
19.1±0.5	29	14.0-22.6	7.7±0.1	6.0-8.8	4.8	14.5
26.4±0.3	29	23.0-30.0	10.4±0.1	9.0-11.8	6.6	17.0
35.4±0.8	12	31.0-40.4	13.2±0.3	12.0-15.0	9.0	28.3

[y]dbh=diameter at breast height.
[z]N=number of trees.

Chapter 12

Citizen attitudes toward orangestriped oakworm: impact, control, host aesthetics and IPM practices

Introduction

Surveys are effective in determining public knowledge of target pests and evaluating control and management practices (Wood et al. 1981, Roden & Surgeoner 1986, Lemke & Kissam 1989). A survey by Byrne et al. (1984) revealed the negative public attitudes toward arthropods and implications for urban pest management. Zungoli & Robinson (1984) surveyed residents and found specific attitudes of the target audience need to be addressed when designing pest management programs. Evaluation of citizen attitudes toward *Anisota senatoria* (J. E. Smith) (Lepidoptera: Saturniidae), orangestriped oakworm, was considered a critical step in developing an integrated pest management (IPM) program.

The objectives of this study were to evaluate public attitudes toward *A. senatoria* and provide a framework for designing an urban IPM program.

Materials and Methods

Ten percent of the homeowners in two Norfolk, VA residential neighborhoods (West Ghent [WG] N=82; Roland Park [RP] N=50) were randomly chosen for interviews (SAS Institute 1985). Rental units were not included in the survey because of a possible bias response. Byrne et al. (1984) found that renters responded more positively to both indoor and outdoor arthropods than homeowners. If a citizen could not be interviewed after two attempts on separate days, then

replacements were interviewed. The survey was conducted by the same person in both areas as a door-to-door interview. There were 18 largely open-ended questions (answers not selected from a list), and time was recorded for each interview. The survey was tested in June, 1988; slight revisions were made in format; and it was conducted in October in the same area but different citizens were interviewed. A competitive market analysis of the two areas was obtained from a local real estate agency to determine real estate values and to estimate incomes (Thomsett 1987).

Descriptive statistics (mean % response) were calculated for each question, and analysis of variance (ANOVA) was conducted to determine differences in responses between the two areas (SAS Institute 1985). Chi-square analysis was conducted to determine significant relationships between questions (SAS Institute 1985).

Results and Discussion

Survey Demographics. Interviews averaged 5.8 ± 0.2 minutes, which were in an acceptable range (Zungoli & Robinson 1984). Mean respondent age was 50.5 years with no significant difference between West Ghent (WG) and Roland Park (RP). Significantly more women were surveyed in WG (74%) than in RP (50%) ($P<0.01$). Sexual difference did not appear to influence the survey, because questions dealt with impact and control and not insect preference or sociological beliefs. Byrne et

al. (1984) found females responded more negatively to arthropods when they were asked how they felt about insects.

Citizens of RP had lived significantly longer at their residence than WG citizens (46% and 27% lived at their residence greater than 24 years respectively) ($P<0.01$). However, this was not a factor in evaluating *A. senatoria* impact because defoliation was most severe from 1986 to 1988, and most citizens were familiar with damage.

A competitive market analysis of the two areas showed homes located in WG were significantly higher in price ($P<0.0001$)($N=53$, median=\$127,500) compared with homes in RP ($N=33$, median=\$68,000). West Ghent and RP median incomes were estimated to be \$51,000 and \$27,200, respectively, based on home purchases averaging 2.5 times annual household gross income (Thomsett 1987). These income differences may have influenced citizen response to *A. senatoria* control.

A. senatoria **impact.** The majority of residents (98.5%) responded affirmatively when they were asked, "Has this insect (*A. senatoria* fifth instar photograph) been a serious problem to the trees in your yard?" These data indicated citizens correctly identified *A. senatoria* as the major shade tree defoliator in Norfolk, VA. Citizen responses were not influenced by the presence of *A. senatoria* larva because the survey was conducted 2 months after larva activity. Time of year when surveys are conducted can influence survey outcome,

depending on insect abundance and biology. Robinson & Bao (1988) showed residents surveyed in August considered *Periplaneta fuliginosa* (Serville) (Orthoptera: Blattidae), smokybrown cockroaches, to be a more serious problem than residents surveyed in April because *P. fuliginosa* was more abundant.

Anisota senatoria impact was shown by the amount of damage (Table 1). Citizens were shown color photographs of trees which had received 15, 25, 50, 75, and 100% defoliation by *A. senatoria* (0% was provided verbally as a choice) (Questions 3 and 4). The majority of citizens (56%) had experienced at least 50% defoliation during a 3 year period with RP citizens experiencing significantly more damage than WG citizens (24% observed total defoliation) (Table 1). Equal responses were given between acceptance of 0, 15, and 25% damage (Table 1). Most citizens (70%) were willing to accept limited *A. senatoria* damage. An IPM program utilizing an aesthetic injury level was developed partly based on this citizen tolerance of *A. senatoria* damage (Coffelt & Schultz 1990b).

There was a significant relationship between the amount of damage citizens experienced (Question 3), and how much citizens were willing to accept (Question 4) (X_2=78.5, P<0.0001). The greater the damage, the less tolerant citizens

were to *A. senatoria* infestations. Zungoli & Robinson (1984) stated tolerance levels are variable depending on the extent of pest infestation. They found the opposite relationship with the *Blattella germanica* (L.) (Orthoptera: Blattidae), German cockroach; the larger the infestation, the greater the tolerance level. When designing an urban IPM program, the relationship between damage and tolerance levels for each pest must be established.

Anisota senatoria impact was evaluated by citizen response to the question "Did you notice frass or droppings falling from your trees?" Most citizens (84%) noticed frass accumulating on area streets and sidewalks and RP citizens were significantly ($P<0.10$) more aware of frass than WG citizens. This could be because RP trees had more defoliation and concurrent frass accumulation. There was a significant relationship between a citizen's attitude that *A. senatoria* was a serious problem, and whether frass was observed ($X_2=18.1$, $P<0.0001$). Citizens complained that frass was a major nuisance and the time spent sweeping and cleaning it from sidewalks and driveways was considerable. Citizens averaged 3.7 hours per week during August and September sweeping frass from their property and RP citizens spent significantly ($P<0.10$) more time sweeping frass (6.8 hours) than WG citizens (1.3 hours).

There were nonsignificant (P>0.10) responses between areas when citizens were asked to name the worst problem associated with *A. senatoria* damage. Citizens disliked *A. senatoria* fifth instars crawling on their property seeking suitable habitats to pupate (Mean = 39%), and were slightly less offended about defoliation impact (Mean = 36%). Despite the considerable time spent sweeping frass, it received the lowest response (Mean = 22%). Citizens observed that *A. senatoria* nuisance infestations were worse than actual defoliation damage. The physical impact of *A. senatoria*, as measured by caterpillars crawling and frass, received a higher total response (61%) than defoliation impact (36%).

A. senatoria **control.** Citizen perception of *A. senatoria* damage to trees on public property was evaluated by their desire for pesticide application. When citizens were asked if they ever called city officials to request *A. senatoria* pesticide application, 61% responded affirmatively. This was a public service provided at no cost. Over half of the citizens (54%) would hire a professional to treat their private or city trees if city officials did not spray (Table 2).

A measure of pest status can also be determined by willingness to pay for treatment. Significantly more citizens of WG would hire a professional (66%), and they were willing to pay more than RP citizens ($56 and $21, respectively)

(Table 2). Although RP citizens had experienced significantly more damage, they were less willing to pay for control, possibly because they had lower income. Lemke & Kissam (1989) found willingness to pay for *Solenopsis invicta* (Buren) (Hymenoptera: Formicidae), red imported fire ant, control was directly related to income.

Effectiveness of *A. senatoria* chemical control was evaluated by asking citizens if it was possible to eradicate *A. senatoria* on their city or private trees. Roland Park citizens experienced more damage and requested more treatment than WG citizens, and they were significantly ($P<0.05$) more cognizant (62% versus 44%) that eradication was impossible. When RP and WG citizens were asked why *A. senatoria* was not controlled, many (Mean = 42.5%) said pesticide application was not timed to *A. senatoria* life stages. City officials based their treatment schedules on citizen demand, which proved ineffective. Improved *A. senatoria* control was achieved by replacing this policy with pest management strategies (Coffelt & Schultz 1990b). Other perceived reasons for ineffective *A. senatoria* control included weak chemicals, too many caterpillars, inadequate pesticide coverage within the tree, improperly trained applicators, the need for area wide coverage of private trees, and insecticide resistance.

Host aesthetics. Citizen attitudes toward aesthetic value of urban shade trees was evaluated. Both survey areas

had a mean of two *Quercus* (oak) species per property. Citizens were asked to choose the most important component in their landscape (Table 3). Trees (35%) and lawns (34%) received the highest mean response. However, significantly more RP citizens considered the lawn (42%) the most important, while WG citizens considered trees (36%) more important than lawns (22%). Roland Park citizens experienced more damage, frass, and pesticide applications, and several citizens stated trees were a nuisance because of high maintenance requirements. Several RP citizens felt the disadvantages of urban shade trees exceeded the benefits, and some requested that oaks be removed. The benefits of urban shade trees have been well documented (Federer 1976, Starkey 1979); however, these data show insect infestations adversely affect tree aesthetic value and citizen perception of the benefits.

Citizens were asked the amount of time they spend caring for trees and shrubs (not the lawn) each week. Differences were not significant ($P>0.05$) between areas (WG=2.4, RP=3.2 hours per week), although citizens differed in their evaluation of tree importance (Table 3). This indicated RP citizens felt tree care was important and applied water and fertilization treatments. When asked if *A. senatoria* defoliation would kill their trees, 73% responded affirmatively. Citizens felt defoliation in August and September was serious and mortality could occur. This

attitude contradicts research that indicates late season defoliation has less physiological impact on tree vigor than early season defoliation (Wargo 1981). However, in 1988, three mature RP trees that had received 4 years of successive *A. senatoria* defoliation died, although other factors such as physiological stress and disease may have contributed to tree mortality.

IPM practices. Citizen attitudes toward IPM practices such as nonchemical or natural control and pesticides were surveyed. Natural control was considered to be a viable IPM strategy, as evidenced by 80% of the respondents willingness to pay a user fee for such a program (Table 4). Most citizens were familiar with natural control, and question clarification was not needed. Significantly more WG citizens were willing to pay for such a service, probably because of higher estimated incomes. Frankie & Levenson (1978) surveyed people in Dallas, TX during 1975-1976 and found 30% had knowledge of nonchemical methods to control insects, and 70% were aware of beneficial insects. In the 14 years since their survey, these data suggest public perception of natural control has increased, although regional and sampling differences may exist.

There was a significant relationship between the IPM strategies of accepting tolerance levels and accepting natural

control (X_2=69.5, P<0.0001). If a citizen accepted the concept of tolerance levels for *A. senatoria* defoliation, then natural control was also acceptable. These responses indicate that IPM tactics such as aesthetic thresholds and injury levels are viable options.

When RP and WG citizens were asked if they felt that pesticides were unsafe, 38.5% responded affirmatively (Table 4). This was lower than expected because of the national publicity over pesticide use. Negative attitudes toward pesticides has increased since Frankie & Levenson (1978) conducted their survey (12% felt chemicals were unsafe). Some RP and WG citizens were unsure about pesticide safety (mean = 25.5%), illustrating the need for educating residents on disadvantages and advantages of pesticides. There was a significant relationship between citizens willing to pay for natural control and their response to pesticides being unsafe (X_2=46.6, P<0.0001). Citizens who felt natural control would help control *A. senatoria* also felt pesticides were unsafe.

Citizen education. Educating the target audience and determining where they obtain their information is important when designing urban pest management programs (Byrne et. al 1984, Zungoli & Robinson 1984). The majority of citizens (77%) obtained information about pest control, primarily from four sources: nurseries (15%), pest control operators (14%),

Norfolk Bureau of Parks and Forestry (13%), and Virginia Polytechnic Institute and State University Cooperative Extension Service (11%). Frankie & Levenson (1978) surveyed Dallas, TX residents and found pest control operators and nurseries provided 43% and 20%, respectively, of all public information. Although lack of formal training in entomology from these two sources was apparent, residents were satisfied with results. The VPI & SU Cooperative Extension Service (11%) and Agricultural Experiment Station (6%) served as information sources for 17% of residents in our study. Educational programs will enhance efforts to effectively manage *A. senatoria* populations.

These data showed that conducting a citizen survey was an important first step when developing urban IPM programs. The response to survey questions on *A. senatoria* impact and control were incorporated into a pest management program (Coffelt & Schultz 1990b).

Table 1. Citizen response to pictorial Question 3 "How much damage did this insect (*A. senatoria*) do to your *Quercus* trees this year or the last 2 years?" and Question 4 "How much *Quercus* damage by *A. senatoria* would you be willing to accept?"

% damage	% Responding Question 3[a] WG[b]	RP	Question 4 WG	RP
0	4	2	30	30
15	18	10	33	30
25	29	24	28	28
50	32	32	4	12
75	5	8	1	0
100	12	24	4	0

[a] Significant difference between areas ($P<0.05$).
[b] WG=West Ghent, RP=Roland Park.

Table 2. Citizen response to Question 5 "If the City of Norfolk did not spray, would you hire a professional pest control operator or tree service?" and Question 6 "How much would you be willing to pay per tree to have a professional spray?"

Question 5[a] Response	% Responding WG[b]	RP
Yes	66	34
No	33	64
Not sure	1	2
Question 6[a] $/tree		
0	34	66
1- 50	27	14
51-101	32	16
102-152	3.5	4
>153	3.5	0
Mean ($)	56	21

[a] Significant difference between areas (P<0.001).
[b] WG=West Ghent, RP=Roland Park.

Table 3. Citizen response to the question "Which of these do you think is the *most* important?"

Character	% Responding[a] WG[b]	RP
Attractive lawn	27	42
Attractive trees	36	34
Attractive shrubs	22	12
Not sure	15	12

[a] Significant difference between areas (P<0.10).
[b] WG=West Ghent, RP=Roland Park.

Table 4. Citizen response to Question 7 "Would you be willing to pay $10 to help control *A. senatoria* with nonchemical or natural control agents?" and Question 8 "Do you think the pesticides sprayed on your trees are unsafe?"

	% Response			
	Question 7[a]		Question 8	
Response	WG[b]	RP	WG	RP
Yes	89	64	39	38
No	7	26	34	38
Not sure	4	10	27	24

[a] Significant difference between areas ($P<0.01$).
[b] WG=West Ghent, RP=Roland Park.

Appendix 1
Anisota senatoria Survey

Location _____

Date ___ No. _____ Time _____

Introduction: Hello, I am Mark Coffelt, a graduate student at Virginia Tech. Can I ask you some questions about insects around your house?

1. Has this insect (oakworm picture) been a serious problem to the trees in your yard? ____yes ____no ____ns

2. Have you ever called the city or a pco to spray your/city trees? ____yes ____no ____ns

3. How much damage did this insect do to your/city trees this year? If none this year, the last 2 years. (pictures)

0	(0%)	____	Fig. 1	(1-15%)	____
Fig. 2	(16-25%)	____	Fig. 3	(26-50%)	____
Fig. 4	(51-75%)	____	Fig. 5	(76% +)	____

4. How much damage would you be willing to accept? (pictures)

0	(0%)	____	Fig. 1	(1-15%)	____
Fig. 2	(16-25%)	____	Fig. 3	(26-50%)	____
Fig. 4	(51-75%)	____	Fig. 5	(76% +)	____

5. About how many mature caterpillars do you think causes this (above) damage?

0 ___ caterpillars Fig. 1 ____ caterpillars

Fig. 2 ___ caterpillars Fig. 3 ____ caterpillars

Fig. 4 ___ caterpillars Fig. 5 ____ caterpillars

6. Do you notice "frass"/droppings falling from your/city trees? ____yes ____no ____ns

If yes, how much time do you spend/wk cleaning it up?

No. hrs./wk ____

7. What do you think is the worse thing/problem associated with oakworm damage to your/city trees?

1. Loss of lvs/shade ____
2. Caterpillars crawling on property ____
3. Frass ____
4. Other: _____

8. Do you think oakworm will kill your/city trees?

____yes ____no ____ns

9. Do you think it is possible to kill all the oakworms on your/city trees? ____yes ____no ____ns

   If no, why not?

   1. Improper spray timing ____ 2. Not strong chemical ___

   3. Too many to kill ____ 4. Other ___

10. If the city of Norfolk did not spray, would you hire a professional pest control operator or tree service?

    ____yes ____no ____ns

11. How much would you be willing to pay/treee to have a professional spray? $_____

12. Which of these do you think is most important?

    1. Attractive lawn ____

    2. Attractive trees ____

    3. Attractive shrubs ____

    4. Not sure ____

13. About how much time do you spend caring for your/city trees and shrubs (not the lawn) each week?

    No. hrs ____

14. Where do you get information on pest control for your/city trees and shrubs?

1. Ext. Ser.	_____	2. Res. Stn.	_____
3. Pks. Rec.	_____	4. Club	_____
5. PCO	_____	6. Other	_____

15. Would you be willing to pay $10 to help control the oakworm with nonchemical or natural control agents?

___yes _____no _____ns

16. Do you think the pesticides sprayed on your/city trees are unsafe? ___yes ___no ___ns

17. How long have you lived at this residence? ___yrs

18. Can you tell me how old you are? _____yrs _____no

19. 1). M___ 2). F___

20. No. oak trees on property: _____

Code: yes - 1, no - 2, not sure - 3

Chapter 13 - SUMMARY

The orangestriped oakworm, *Anisota senatoria* J. E. Smith (Lepidoptera: Saturniidae), has become a major oak pest in southeastern VA. Information on *A. senatoria* ecology, behavior, impact and alternative control strategies that emphasized integrated pest management (IPM) have not been previously documented. Therefore, studies were undertaken in four main areas including *A. senatoria* ecology, behavior, impact and the potential use of IPM strategies.

The ecological studies had three objectives. First, the within-tree distribution and dispersion of *A. senatoria* was studied and a sampling plan developed during a 3 year study. Within-tree distribution of *A. senatoria* life stages showed there were significantly more eggs and early instars (first-second) in low strata (1.7-3.6 m in height) compared with middle and high strata. Therefore, recommendations were made that only the low strata receive pesticide applications for control of the susceptible egg stage and early instars. Dispersion indices showed Taylor's power law provided a better fit to *A. senatoria* count data compared with Iwao's patchiness regression. Taylor's power law indicated that aggregation was greatest among early instars, followed by third instars and late instars. A fixed-precision-level sampling plan was developed that determined the minimum number of oak tree samples necessary to estimate the number of eggs and early

instars present in low strata.

In the second ecological study, the influence of the tree growth regulator paclobutrazol on the growth of willow oak, *Quercus phellos* L. was investigated from 1988 to 1990. The influence of paclobutrazol on the development and survival of *A. senatoria* was also determined. Paclobutrazol significantly reduced *Q. phellos* growth, especially one and two years posttreatment. The most significant paclobutrazol effects on *A. senatoria* development and survival were measured one year posttreatment. Early and late instars differed in their response to paclobutrazol treatments. In laboratory studies one year posttreatment, the paclobutrazol treatment at the highest rate slowed development and decreased survival of third instars compared with control treatments. Paclobutrazol treatments at the two lower rates significantly increased survival for late instars and prepupae in the laboratory compared with the paclobutrazol treatment at the highest rate. Accelerated development occurred in the fifth instar with paclobutrazol treatments. Paclobutrazol treatments at the lowest rate significantly increased female pupal weights in the laboratory and field. These data suggested that *Q. phellos* injected with paclobutrazol at the lowest rate may experience a more healthy late instar population, as measured by increased survival, development, and female pupal weight.

The third objective examined several biological

characteristics of *A. senatoria*. The most significant results indicated that egg mass size was large, and that there were more eggs per egg mass oviposited on *Q. palustris* Muench., pin oak, (mean=493.5) compared with *Q. phellos* (mean=370.2). High pupal mortality occurred and only 1.2% of the pupae produced adults. Pupae were capable of overwintering for two years in the field. The first report of a second generation from September-November was documented. Second generation *A. senatoria* adults oviposited more egg masses, larvae infested more trees and had a longer development time compared with the first generation. Large egg mass size, pupae that were capable of overwintering for two years and the presence of a second generation may partially explain the consistent *A. senatoria* populations that have occurred in southeastern VA.

The ethological studies examined *A. senatoria* gregarious behavior. Laboratory and field data showed increased *A. senatoria* survival in early instars (first-second) with increased group size. A critical group size was defined as the number of larvae where significant mortality no longer occurred. In the laboratory, critical group sizes were one to three larvae, while in the field, between 25 and 50 larvae were required. Lower survival in smaller groups was attributed to decreased feeding facilitation, silk production, parasite activity, and increased predation.

The third study area examined *A. senatoria* defoliation

impact and frass production. The hypothesis that late season defoliation by *A. senatoria* caused a significant depletion in oak growth and vigor was tested from 1987-1990. Oak growth was measured on three oak species planted in fabric containers. After 3 and 4 years of 100% defoliation, *Q. palustris* had significantly less top growth, caliper growth and root dry weight compared with undefoliated trees. *Quercus phellos* that experienced 3 and 4 years of defoliation had significantly less top growth compared with undefoliated trees. *Quercus rubra borealis* (Michx. f.) Farw., northern red oak, grew poorly and was unaffected by late season defoliation. In a related study, two oak species planted in the urban landscape were sampled for root starch as an indicator of tree vigor. Starch content and tree vigor in *Q. palustris* was significantly reduced by increased defoliation, and some tree mortality occurred. *Quercus phellos* was a hardier species compared with *Q. palustris* and was not significantly affected by consecutive late season defoliations. In addition, data suggested that *Q. palustris* was affected more by *A. senatoria* late season defoliation when trees were planted in stressed urban sites. These data have important implications for *A. senatoria* management strategies. *Anisota senatoria* populations that cause 100% late season defoliation on *Q. palustris* should be monitored to prevent progressive decline in tree health.

Sampling frass provided a decision-making guideline for *A. senatoria* management. Landscape fabrics recovered 90% of all frass deposited and fabrics provided a reliable sampling method. Frass length was used to differentiate *A. senatoria* instars reared on *Q. palustris*. Frass length and amount were also used to indicate host plant preference by *A. senatoria* larvae. Frass length was significantly longer in all instars when larvae were reared on *Q. nigra* L., water oak, *Q. phellos*, *Q. coccinea* Michx., scarlet oak, and *Q. palustris*; and significantly shorter when reared on *Q. alba* L., white oak. The weight of *A. senatoria* frass per 2.62 m^2 landscape fabric predicted defoliation of small *Q. palustris*.

The last study area examined IPM strategies and included five objectives. First, parasitism of *A. senatoria* life stages was determined. The most abundant egg parasite was a new species of *Aprostocetus* and mean egg mass parasitization was 24.6%. The eupelmid *Anastatus hirtus* (Ashmead), a new host record, parasitized a mean of 11.7% of *A. senatoria* egg masses. The encyrtid *Ooencytrus* sp., also a new host record, had a mean egg mass parasitization of 0.09%. Inundative releases of *Trichogramma minutum* (Riley) in 1989 and 1990 did not increase parasitism rates and mean egg mass parasitization was 2.3%. Parasitism of first generation *A. senatoria* egg masses was higher compared with second generation. The four

egg parasite species collected in this study parasitized 30% of *A. senatoria* egg masses and within egg mass parasitization was 7.9%. Larval parasitization by *Hyposoter fugitivus* (Say) and *Apanteles* sp. averaged 3.2% and 9.3% in first and second generation *A. senatoria* populations. Mean tachinid parasitization of larval *A. senatoria* by *Lespesia anisotae* (Webber) and *Belvosia bifasciata* (F.) was 10.7% and 0.7%. *Lespesia aletiae* (Riley) was recovered in 1990 from prepupae and was a new host record. Parasite effectiveness was decreased by eight hyperparasites of *A. senatoria* larvae. *Perilampus hyalinus* (Say) parasitized 2.0% of *L. anisotae* and 23.5% of *B. bifasciata* larvae. Hyperparasites that were new host records included *Brachymeria ovata* (Say), *Eupelmus cyaniceps* (Ashmead), *Isdromas lycaenae* (Howard), and *Horismenus* species. First and second generation *A. senatoria* larvae experienced 40 and 33.6% hyperparasitism. These relatively low parasitization rates may partially explain the presence of consistently high *A. senatoria* populations.

Second, host plant preference among *Quercus* species was determined. Survival, rate of development, and oviposition of *A. senatoria* were greatest in *Quercus palustris*, *Q. coccinea*, *Q. phellos* , and *Q. acutissima* Carruth. (sawtooth oak); intermediate in *Q. rubra borealis*, *Q. bicolor* Willd. (swamp white oak), *Q. prinus* L. (chestnut oak), *Q. falcata* Michx. (southern red), *Q. macrocarpa* Michx. (bur oak), and *Q. nigra*;

and poorest in *Q. alba*. Planting least preferred species in the urban landscape, like *Q. alba*, may contribute to lower *A. senatoria* populations.

The third objective determined citizen attitudes toward *A. senatoria* and IPM practices. A random survey of two Norfolk, VA residential neighborhoods determined the amount of defoliation that citizens were willing to tolerate. These attitudes provided a framework for designing an urban IPM program for *A. senatoria* in the urban landscape.

The fourth objective established an aesthetic injury level (AIL) of 25% defoliation. Monitoring and implementing the AIL in 1988 resulted in a decrease in pesticide volume of 80% and a real cost savings of 55% over the previous year.

The last objective quantified an AIL and threshold for *A. senatoria* that infested different sized *Q. palustris*. There was a significant linear relationship between a threshold based on the number of *A. senatoria* egg masses and an AIL based on 25% defoliation of *Q. palustris*. Thresholds of 0.9 egg masses predicted 25% defoliation (AIL) of trees with a mean diameter at breast height (dbh) of 12.6 cm; 4.8 egg masses for trees with a mean dbh of 19.1 cm; 6.6 egg masses and a mean dbh of 26.4 cm and 9.0 egg masses for trees with a mean dbh of 35.4 cm. Quantification of an AIL and threshold provided a practical decision-making guideline for an integrated pest management program for *A. senatoria*.

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VITAE

Mark Alan Coffelt was born in Davenport, Iowa on November 8, 1958 and attended Iowa State University majoring in Fisheries & Wildlife Biology & Pest Management, graduating in 1981 with a B. S. degree. He worked for a pest management firm scouting field crops for his B. S. internship program. He then attended the University of Nebraska on a teaching assistantship and graduated in 1985 with a M. S. in Entomology. His research investigated the bionomics of a honeysuckle aphid.

He accepted a position as agricultural research scientist with Virginia Polytechnic Institute and State University, Hampton Roads Agricultural Experiment Station, Virginia Beach, Virginia on March 1, 1985. He provided technical support to Dr. P. B. Schultz and began work on his Ph.D in Entomology in 1987. His research examined the ecology, behavior, impact, and an integrated pest management strategy for the orangestriped oakworm in the urban landscape. He was appointed adjunct faculty and instructor at Christopher Newport College, Newport News, Virginia in 1988. He is a member of several professional organizations, including Sigma Xi and Phi Kappa Phi.