POPULATION DYNAMICS OF OVERWINTERING LIFE STAGES

OF THE ALFALFA WEEVIL, HYPERA POSTICA (GYLLENHAL)

by

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(ABSTRACT)

Virginia is a natural laboratory for studying overwintering habits of the alfalfa weevil. At higher elevations, winters are relatively harsh and weevil pressure on the alfalfa crop is usually light. Much heavier pressure is the rule at lower elevations where winters are milder. The goal of this study was to examine the effects of fall and winter temperatures, parasites, and fall regrowth management on population dynamics of overwintering stages of this insect. Sixteen commercial alfalfa fields in Montgomery Co. (elevation 610 m) and Bedford Co. (elevation 300 m) were used in the study. Approximately half the fields each year were either harvested or grazed to remove fall regrowth. In the other fields, fall regrowth was left standing through the winter.

Six different pitfall trap designs were compared for collection efficiency, installation and servicing effort, and cost. Barrier traps outperformed the other trap designs and were inexpensive and easy to install and service. Sweepnet

samples were used to monitor weevil adults during their fall migration. A newly designed sampling devise which removes all plant material, litter, and approximately 2 cm of soil from a 1/20 m^2 area, was used to measure absolute densities during fall and winter. Based on these absolute density samples fewer adults overwintered within fields in which fall regrowth was removed.

Dissections revealed the presence of three parasites: _Hyalomyodes triangulifer_ (Loew), _Microctonus aetheopoides_ Loan, and _M. colesi_ Drea. Total parasitization rates were low. The highest measured rate was 16.1% in Bedford Co. in 1984-85. Female reproductive development also was determined through dissection. Females reach sexual maturity shortly after returning to alfalfa fields in the fall. Most contain full-size eggs in their oviducts from late fall through the winter.

Egg densities as measured by laboratory incubation of field collected plant material indicated no differences related to elevation in early February, but significantly more viable eggs were present by late March at the low elevation site. In 1984, Bedford Co. samples indicated significantly more eggs in fields receiving no fall regrowth management.

A simulation model called OAWSIM (Overwintering Alfalfa Weevil Simulation) was developed to examine the influence of factors which affect overwintering life stages. Model predictions indicate fall and winter temperatures, and fall regrowth management are major influences on the population dynamics of this insect.

DEDICATION

I dedicate this dissertation

to my wife, Lucy

and

daughter, Alison

Thank you

for your love

and support.

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INTRODUCTION

Alfalfa is a high protein forage crop grown to feed livestock. In 1980, fields totaling 40,000 ha were present in Virginia (Anonymous 1982). The alfalfa weevil, *Hypera postica* (Gyllenhal) (Coleoptera:Curculionidae) feeds on the first cutting in the spring and can cause serious damage.

This pest is now distributed throughout the continental United States and parts of Canada and Mexico. It is native to parts of Europe and Asia and was accidentally introduced to this country on three separate occasions. The first introduction was found near Salt Lake City, UT in 1904. Titus (1910) originally identified it as *Phytonomus posticus* Gyllenhal. The synonym *Hypera postica* (Gyllenhal) was later adopted. A second introduction near Yuma, AZ was discovered in 1939 (Wehrle 1940), but the insect was misidentified as the Egyptian alfalfa weevil, *H. brunneipennis* Boheman. A final introduction occurred in Maryland around 1945 (Poos and Bissell 1953) and this strain spread into Virginia in 1952 (Evans 1959). Though a rickettsia causes partial incompatibility between eastern and western strains, today we know that all three introductions were of the same species, *H. postica* (Hsiao and Stutz 1985, Hsiao and Hsiao 1985, Hsiao and Hsiao 1984).

Crop losses to alfalfa weevil feeding were once high throughout its range but a biological control program begun in 1959 by the U.S. Department of Agriculture has resulted in establishment of six parasites. In states north of Virginia and east of Ohio these biological control agents have largely eliminated the need for insecticides (Day 1981). In parts of Virginia and in states farther south, the alfalfa weevil remains a serious pest in spite of the presence of these parasites. There is evidence suggesting this regional difference may be related to the variable importance of fall and winter-laid eggs.

Virginia is a natural laboratory for studying overwintering of the alfalfa weevil. At high elevations within the state winters are relatively harsh and the climate is not unlike that in more northerly states. In contrast, at low elevations winter temperatures are mild and the climate is similar to that in more southerly states. The following research was designed to examine the influence of winter temperatures, fall regrowth management, and parazitization on overwintering life stages of the alfalfa weevil in Virginia.

CHAPTER 1: LITERATURE REVIEW

LIFE CYCLE

Alfalfa weevil eggs normally hatch in the spring. Hatching requires the equivalent of about twelve days at 21°C (Evans 1959) or 117.2 degree days above the developmental threshold of 7.2°C (Gutierrez et al. 1976). Since no cold shock is required, it is not uncommon to find small numbers of larvae in fall and winter (Campbell et al. 1961, Bass 1967, Pitre 1969). Inadequate food and adverse weather generally prevent these individuals from reaching maturity. Most eggs hatch after the weather has moderated and the alfalfa has begun to grow. First instars crawl to the terminals and initiate feeding in the buds and unfolding leaves.

Under favorable conditions the larvae develop quickly through four instars. Developmental temperature thresholds and degree day requirements have been determined by Casagrande and Stehr (1973) and Gutierrez et al. (1976). After about three weeks of feeding they pupate in white, net-like cocoons. Approximately ten days later new adults emerge. They feed briefly before moving to suitable aestivating sites usually outside the alfalfa fields. Migration from alfalfa fields is a response to harvest which creates an unfavorable environment for the weevils (Prokopy and Gyrisco 1965). Large numbers of adults will remain in the fields if the alfalfa is left unharvested (Manglitz 1976).

In their search for shelter, migrating weevils launch themselves from the tops of alfalfa plants during the evening hours when the light has begun to fade but the temperature is still warm. They are weak flyers and tend to fly passively with the wind at a height of about 7 m (Prokopy and Gyrisco 1965).

In Virginia the peak spring flight period is in May or June (Pamanes and Pienkowski 1965) and coincides with the first cutting. The timing varies along a north-south gradient. In New York and northern Utah where weevil development is later relative to the crop, most adults remain in the fields until the second cutting (Southwick and Davis 1968, Prokopy and Gyrisco 1965).

Tall trees seem to act as partial barriers and many weevils find shelter in surface litter and soil under trees and fence rows bordering alfalfa fields (Manglitz 1958, Prokopy et al. 1967). Not all weevils choose surface litter or soil, the Egyptian strain often finds shelter under loose bark of the eucalyptus tree (Christensen et al. 1974).

Aestivating weevils are in a state of diapause. Their respiration rate is lowered (Tombes 1964) and their sexual development is considerably arrested (Guerra and Bishop 1962). Diapause is triggered by the combined effects of temperature and photoperiod (Schroder and Steinhauer 1976, Rosenthal and Koehler 1968).

The return migration begins in mid-October and is largely complete by mid-November in Virginia. Again the timing varies with latitude. In New York fall migration begins in September (Prokopy and Gyrisco 1963, Prokopy et al. 1967), while in some regions it is delayed until spring (Tysowsky and Dorsey 1970, Simpson and Welborn 1975). Photoperiod apparently plays little if any role in initiating fall movement. The daily difference between maximum and minimum temperatures is the most important factor at least for the Egypian strain (Christensen et. al. 1974).

A fall flight period has been detected by several researchers (Prokopy and Gyrisco 1963, Pamanes and Pienkowski 1965), but it is not clear whether they fly from aestivating sites to alfalfa fields or crawl to the fields then fly after replenishing their energy stores. There is evidence for both theories (Barney et al. 1978, Blickenstaff 1967, Pausch et al. 1980) and it seems likely that some weevils, especially those in nearby aestivating sites, crawl back while others fly if their energy stores are adequate. They seem to rely primarily on vision for locating alfalfa fields. Meyer's (1975) calculations indicate they can see a 0.4ha alfalfa field from a distance of 70 m. They are attracted to the smell of alfalfa over short distances (Pienkowski and Golik 1969).

Upon their return, the adults resume feeding. Over its lifetime each adult will consume four and a half times as much as it did as a larva (Bjork and Davis 1984). In the fall this injury goes completely unnoticed, but if large numbers of adults are feeding at harvest time in the spring they can delay emergence of new growth, sometimes necessitating the use of stubble sprays. Once their energy stores are replenished and their sexual development completed, mating activity begins.

A sex pheromone has never been described from this species and there may not be one as males will readily mount other males or even other species of curculionids (LeCato and Pienkowski 1970). In the laboratory multiple matings are the norm and females mated more than once lay larger numbers of fertile eggs (LeCato and Pienkowski 1972). Mounting frequency and duration are greatest at 10°C, though mating can occur at temperatures just above freezing (Day 1971, LeCato and Pienkowski 1970). In the field, copulating adults have been collected under four inches of snow (Campbell et al. 1961). The presence of sperm in the spermatheca initiates oviposition within 72 hours (LeCato and Pienkowski 1972).

Eggs are laid primarily in the stubble and fresh stems of alfalfa. Gravid females puncture the stem with their mouthparts, then insert their ovipositor into the hole and deposit a cluster of eggs. An average cluster consists of 9.5 eggs (Burbutis et al. 1967, Niemczyk and Flessel 1970).

Besides alfalfa, several clovers are suitable hosts for egg laying (Michelbacher and Essig 1934), as well as nine common weed species, especially henbit, Lamium amplexicaule L. and shepherdspurse, Capsella bura-pastoris (L.). Even when green stems are available a large proportion of the eggs are laid in stubble and dead plant material (Niemczyk and Flessel 1970, Gutierrez et al. 1976).

The alfalfa weevil has extraordinary reproductive potential. The maximum oviposition rate in the lab occurs when temperatures fluctuate between 4.5°C and 15.5°C (LeCato and Pienkowski 1972) and a single female can produce over 6000 eggs in her lifetime (Coles and Day 1977). Oviposition begins in the fall, continues on warm winter days, and extends well into the spring. The milder the climate the more eggs are laid in fall and winter (Woodside et al. 1968, Roberts et al. 1970). Only about 2% of total oviposition occurs in the fall in Wisconsin (Litsinger and Apple 1973), while an estimated 50% of the eggs in Virginia are deposited in the fall (Evans 1959).

Under certain conditions a partial second generation may be produced. Eggs laid early in the fall sometimes hatch and if the weather is favorable, some individuals are able to complete their development before winter arrives (White et al. 1969). More recently in Ontario, adults have been detected which matured sexually and laid eggs in the summer without going into aestivation (Loan et al. 1983).

OVERWINTERING

Insects are poikliotherms, their body temperature generally reflects the ambient temperature. In temperate climates insects which do not migrate must either find well insulated shelter or adjust their physiology/biochemistry so they can tolerate freezing temperatures. Many insects, including the alfalfa weevil, combine aspects of both systems into a successful overwintering strategy. Baust and Morrissey (1976), Danks (1978), and Hamilton (1985) review overwintering strategies of temperate zone insects.

The alfalfa weevil is somewhat unusual in overwintering in two life stages over much of its range. Adults are hardiest and represent the primary overwintering stage in the northern United States and Canada. In Virginia and states farther south, both eggs and adults overwinter successfully.

Successful overwintering for many insects depends on selection of a suitable microhabitat. Important characteristics include aspect, snow cover, and water content of the surrounding medium (Danks 1978). Fall and winter-laid alfalfa weevil eggs are virtually unprotected from cold winter temperatures. Thin plant stem walls and their proximity to the soil surface offer limited thermal buffering. Alfalfa weevil eggs become increasingly cold tolerant as they develop, however just before they hatch, their tolerance suddenly decreases. Eggs supercool at between -21.9°C and

-25.5°C (Armbrust et al. 1969) and twenty-four hours exposure to -23.3°C will kill 100% (Morrison and Pass 1974).

Physiological or biochemical changes in overwintering insect eggs are probable, but virtually unstudied. Their minute size makes this sort of study difficult. In general insect hemolymph freezes at about -12°C because of the dissolved solutes (sugars, salts, proteins, etc.) which it contains (Hamilton 1985). The demonstrated supercooling ability of alfalfa weevil eggs beyond this temperature indicates there are probably physiological/biochemical changes within them which enhance their overwintering survival.

Alfalfa weevil adults are somewhat better protected from exposure to cold temperatures than their eggs. During harsh weather they burrow through the litter and into the soil often next to alfalfa crowns. In one study, eighty-four percent did not penetrate deeper then 2 cm (Tysowsky and Dorsey 1970). Researchers have reported supercooling points of about -18°C for adults (Peterson 1960, Armbrust et al. 1969) which when combined with the insulating properties of the litter, soil and snow should confer adequate protection from most winter weather. Tysowsky and Dorsey (1970) demonstrated that weevils removed from frozen soil, which appear quite lifeless at first, become active after approximately two hours at room temperature.

Two main physiological/biochemical strategies have been identified by which insects survive subfreezing temperatures.

Many avoid freezing by producing antifreeze compounds which lower the supercooling point of their hemolymph. Others are freeze tolerant and utilize ice nucleating factors to initiate extracellular freezing. This draws water out of their cells thus concentrating the protoplasm to the point where it does not freeze (Hamilton 1985). The demonstrated supercooling point of alfalfa weevil adults indicates that they are at least partially freeze avoiding insects. This aspect of their physiology, however, has never been studied and there is some evidence that they may be freeze tolerant to some degree. Armbrust et al. (1969) reported many adults will survive being frozen if they are warmed slowly. Further study in this area would be very interesting; however, the research is complicated by the difficulty of extracting pure hemolymph from such a small insect and by the recently recognized fact that insects will lose some of their cold hardiness within hours of exposure to warm temperatures (Baust and Morrissey 1976, Baust and Rojas 1985).

NATURAL POPULATION CONTROL

Abiotic factors play a very large, perhaps primary, role in controlling the population dynamics of natural alfalfa weevil populations. Two life table studies have identified larval mortality during establishment and adult mortality during aestivation and overwintering as key factors which determine year-to-year population trends (Latheef et al. 1979, Horn 1975). Abiotic factors are apparently the most important causes of mortality to both groups. Larval establishment is affected by the severity and duration of cold temperature episodes which the developing eggs have endured (Shade and Hintz 1983, Cothran and Gyrisco 1966).

Adult mortality from abiotic causes has received very little study. This reflects two difficulties with research on aestivating and overwintering adult weevils. First it is impossible to observe them in their natural habitat without significantly disturbing it and secondly collecting them with conventional sampling methods is extremely inefficient. One study in New York which seems to confirm the primary importance of climatic mortality to adults employed the use of flat "envelope" cages buried under litter to contain adult weevils and protect them from predators. In these cages only 25% survived the winter with most mortality occurring in January and February (Helgesen and Cooley 1976). Unfavorable conditions also affect oviposition and may cause females to resorb eggs and regress sexually (Day 1971).

Eggs and established larvae can also suffer significant mortality during unusually cold temperatures. In some areas eighty percent or more of fall-laid eggs are routinely killed by winter temperatures (Parks 1914, Blickenstaff et al. 1972), and late frosts can cause substantial mortality to feeding larvae.

Natural enemies of the alfalfa weevil include at least a dozen insects and two fungi. In northeastern states and in Europe, these natural biological control agents effectively prevent weevil populations from reaching damaging levels (Day 1981, Schroder and Dobson 1985).

Alfalfa weevil eggs are attacked by a parasitic wasp, *Pattason luna* (Girault), and by the predaceous thrips, *Frankliniella tritici* (Fitch) (Barney et al. 1979). Egg mortality from these two natural enemies may reach as high as 15% (Streams and Fuester 1966).

Early instar alfalfa weevils are attacked by three parasitic wasps which have been imported into this country as biological control agents. *Tetrastichus incertus* (Ratzeburg), *Bathyplectes anurus* (Thomson), and *B. curculionis* (Thomson) lay their eggs in the weevil larvae. The developing parasites feed on the host's body fluids and tissues, eventually killing it.

Late instars are parasitized by another wasp and by a fungus. This wasp, *Microctonus colesi* Drea, lays its eggs in nearly mature weevil larvae and overwinters within the body of adult weevils (Day 1981). The fungus, *Zoophthora phytonomi* (Arthur) actually infects all larval stages, but disease outbreaks are most likely to be noticed when large larvae are present in high number. The disease can cause dramatic population collapses under certain environmental conditions (Los 1982).

Alfalfa weevil larvae also fall prey to several predators. The ladybird beetle, Coleomegilla maculata DeG., at least two lacewings (Chrysopa spp.), and two damsel bugs (Nabis spp.) are common, naturally occurring biological control agents in alfalfa. Their relative importance has not been determined (Wheeler 1977).

Adult alfalfa weevils are attacked by two parasites, a pathogenic fungus, and several predators. Microctonus aetheopoides Loan lays its eggs in the newly emerged summer weevils and like M. colesi, it overwinters within its host. M. aetheopoides, however, is bivoltine. The first generation parasitizes overwintered adults and develops without diapause. The second attacks newly emerged summer adults and diapauses as a first instar until the following spring (Abu and Ellis 1976, VanDriesche and Gyrisco 1979). Both Microctonus species cause host sterility (Drea 1968).

A native Tachinid, Hyalomyodes triangulifer (Loew), also parasitizes adults. This species attacks several other beetles as well. Adults of this parasite emerge in the spring and are active all summer and well into the fall (Thompson 1954, Wellso and Hoxie 1969).

Adult weevils are also subject to attack by Beauveria bassiana (Balsamo), a pathogenic fungus (Cothran and Gyrisco 1966), at least three species of Carabids, and a cricket (Barney et al. 1979).

AGRONOMIC POPULATION CONTROL

In the South, natural controls often are inadequate to prevent economically important yield losses. Here alfalfa plants have only just begun to grow when fall and winter-laid eggs hatch and the larvae begin to feed. Under favorable conditions they can completely destroy the first cutting. If the plants are able to attain about half their harvest height before feeding becomes heavy, they can tolerate considerable feeding injury. Growers, therefore, need not eliminate weevils from their fields, but ideally they should strive to manage weevil populations so that economic injury levels are never reached. Management practices which delay larval feeding relative to the growth stage of the crop are especially beneficial.

Currently in Virginia most growers who believe they have an alfalfa weevil problem use spring applications of insecticides aimed primarily at the larvae. In 1981, 77% of the state's alfalfa growers were using insecticides in this way and 88% of them sprayed routinely every year (Luna 1981). Carbofuran, phosmet, malathion, methidathion, chlorpyrifos, methyl parathion, and parathion are labeled for this use (Luna 1985). Calendar sprays by themselves are not the most environmentally or economically sound form of alfalfa weevil management. Unfortunately many growers are unaware of other management practices which could reduce their dependence on insecticides. Many of these tactics were developed decades ago before the widespread use of insecticides and most have not been subjected to modern scientific evaluation. Anecdotal evidence and yield figures from earlier studies indicate probable significant weevil suppression. Unfortunately at that time no efficient means were available to sample the weevil life stages (adults and eggs in most cases) being directly impacted by the management practices.

Among the disadvantages of spring insecticidal treatments are their impact on non-target insects and their interference with other critical farm activities, especially spring planting. Los (1982) documented the negative impact of spring treatments on _B_. _anurus_, _B_. _curculionis_, and on carabids which are important predators.

One alternative is fall applications of insecticides aimed at killing newly returned adults before substantial oviposition has occurred. Such treatments should be less detrimental to predators and parasites, and interfere with fewer critical farm activities. Timing might still be important, however, because newly returned adults are most susceptible to insecticides before they have had a chance to replenish their fat reserves (Bennett and Thomas 1963, Bennett and Thomas 1964, VanMeter and Pass 1970).

Fall insecticide applications for alfalfa weevil control are not new, in fact they were once standard practice. During the fifties and sixties when chlorinated hydrocarbons like heptachlor and dieldrin were available, fall applications of granular formulations of these compounds were the recommended way to control this pest (Bass and Blake 1965, Armbrust and Gyrisco 1965, 1966, Pass 1966). The long residual life of these materials meant they could be applied effectively at almost any time including winter and spring (Muka 1957, Dorsey and Quinn 1962). They could even be mixed and applied simultaneously with fertilizers.

In the late sixties the weevil developed resistance to heptachlor and dieldrin and they no longer provided satisfactory control (Adler and Blickenstaff 1964, Dorsey 1966). Fall applications of organophosphates were tested but they were not effective (Pass 1966, Steinhauer and Blickenstaff 1967, Armbrust and Gyrisco 1965). Organophosphates, however, were effective against larvae in spring treatments (Dorsey 1966). Today, besides several organophosphates, the carbamate carbofuran is in widespread use and it's long residual life allows greater flexibility in time of application. Carbofuran can be applied effectively up to 80 days prior to harvest (Summers and Cothran 1972).

A late fall harvest which removes all fall regrowth leaving only stubble to overwinter should theoretically be a useful weevil management tactic. Returning weevils may be less attracted to such fields and the removal of fall regrowth should limit oviposition sites and expose overwintering stages to harsher winter conditions. Though there have been numerous studies of the effects of fall harvest on alfalfa yields and stand persistence, the direct effect on overwintering weevils has not been studied.

Fall harvests can be detrimental to a stand if not timed properly (Jackobs and Oldemeyer 1955, Reynolds 1971). Alfalfa needs a recovery period of about 6 weeks in the fall during which it grows 20-25 cm and replenishes its root carbohydrate reserves (Smith 1972, Mays and Evans 1973). After this period, which generally coincides with the first hard frosts, the alfalfa can be safely harvested (Sholar et al. 1982, 1983, Collins and Taylor 1980). Fall alfalfa hay is fine in texture, loses few leaves while curing, and is generally high in quality (Collins and Taylor 1984, Dexter 1964).

Winter grazing should effect weevil populations in a way similar to fall harvesting. Its benefits have been recognized since shortly after the weevil was introduced (Reeves et al. 1916). Livestock can be turned into the fields during the period from December through February, preferably when the ground is either frozen or dry. Many alfalfa weevil eggs are ingested as the livestock graze. Senst and Berberet (1980) demonstrated significant reductions in eggs in grazed plots versus ungrazed controls. At the same time *B. curculionis* cocoons, which overwinter in the soil surface litter, suffered only 12.2% mortality due to trampling.

Grazing is thus compatible with this other component of a possible integrated pest management approach.

Flaming alfalfa fields enjoyed a brief period of popularity in the 1960's. Flame treatment of dormant stands in late winter helped control alfalfa weevil and winter annual weeds. It also seemed to stimulate alfalfa growth (Chappell and Ellwanger 1969, Pitre et al. 1969). Effective flaming required all dead alfalfa stems and other plant material to be completely burned. In the process, fall and winter-laid eggs and probably some adults were killed. The alfalfa plants were not harmed and in fact seemed to be stimulated by the ash residue which contained nutrients previously tied up in organic matter (Tippins 1964).

There were two types of field flamers. The first consisted of a tractor or trailer mounted LP-gas tank fitted with a one or two row array of downward-pointing burner heads. A wide hood called a hover was sometimes used to concentrate heat from the burners which was supposed to reach at least 1093°C (Chappell et al. 1967). Typically these flamers were 3 to 5.5 m wide and were driven at 1.6 to 4.8 km/hr over a field. Average coverage was 1 to 2 ha/hr. Depending on the pressure used and speed of the tractor, fuel consumption varied from 15 to 61 l/ha.

The second type of flamer was a modification of a regular boom-type pesticide sprayer. A liquid fuel was sprayed on the ground and then ignited by special burners which dragged a meter or so behind the boom. Flamers of this type were less expensive yet apparently just as effective as LP-gas flamers (Falter and Campbell 1968). With either type of equipment the optimal time for flaming was late February or early March, after the largest number of weevil eggs had been laid, but before the alfalfa began to grow. Warm, dry, windless conditions were preferred.

Other cultural practices used before the age of chemical insecticides included winter cultivation and/or brush-dragging to stimulate rapid growth of the first crop (Cooley 1914, Michelbacher and Essig 1935) and flooding to drown overwintering adults and eggs (Reeves 1917).

SAMPLING METHODS

The primary reason why so little is known about the ecology and management of overwintering stages of the alfalfa weevil is that this pest is notoriously difficult to sample in terms of absolute numbers (Armbrust et al. 1980, Armbrust and Gyrisco 1975). It can require hours of patient searching on hands and knees to find a single adult or egg cluster during the winter.

Several trapping methods have been devised which are useful for collecting weevils, but unfortunately they do not measure absolute densities because catches depend on weevil activity levels. Sampling methods which do attempt to measure absolute densities are extremely inefficient. It is not unusual for adult population density estimates to require 3 to 4 man hours per field plus 3 days extraction time in a bank of Berlese funnels (Armbrust et al. 1980). Egg sampling is similarly tedious.

A sweepnet is useful for sampling adults before they leave alfalfa fields in early summer and after they return in the fall while the alfalfa is still green. Even with this method there is a complication; they are most active and most easily captured at night. As long as the temperature is above 5°C their activity level increases as light intensity decreases (Poinar and Gyrisco 1960). Sweeping between 7 pm and midnight is especially productive (Wilson and Armbrust 1970, Bass 1967). A trawl net pulled behind a motorcycle has been developed for mass collection of adults at these times. It is approximately 15 to 20 times more efficient than a sweepnet (Koehler and Rittershausen 1971). These methods are not useful whenever the alfalfa is wet or after the fall regrowth is frost-killed.

Flying weevils are also difficult to sample. Motor driven rotating nets yield very few weevils (Southwick and Davis 1968) and sticky boards or screens, though useful in determining general flight activity levels, do not catch large numbers (Roberts et al. 1978, Prokopy and Gyrisco 1965, Poinar and Gyrisco 1962). Adults are apparently able to avoid these traps in the absence of wind (Sherburne et al. 1970).

Emergence-type traps have been used to determine when adults break diapause and begin their fall migration (Roberts et al. 1978, Cothran et al. 1972). These traps consist of light-proof boxes or tents to which clear grass jars containing killing agents are attached. Active weevils on the ground crawl up the sides of the trap toward the light until they enter the jar and are killed. Traps of this type are useful for collecting overwintering weevils (Miller et al. 1972, Arunin 1974), but since catches are affected by activity level and insects may enter from outside the enclosed area, they are not useful for measuring absolute densities.

Pitfall traps are yet another relative sampling method affected by weevil activity levels. They are, however, effective for collecting overwintering adults and they have been used in migration studies (Pamanes and Pienkowski 1965, Pausch et al. 1979).

A suction device known as the D-vac is of some use in sampling adults. This device is usually carried on a backpack but it can be mounted on a simple 2-wheeled cart (Dietrick et al. 1959, Dietrick 1961, Schroder 1970). A 1 ft^2 suction head is standard, though a 1/2 ft^2 size offers more powerful suction and may be more efficient (Guppy and Harcourt 1977). The D-vac is able to sample adults no matter how short the alfalfa. Under ideal conditions it will collect 75% of the weevils which are on the plants or soil surface (Stevens and Steinhauer 1973). It will not collect weevils which have burrowed down into the soil.

Several techniques have been developed for collecting weevils from soil and these are sometimes used in conjunction with a D-vac. Pitre (1969) simply used a shovel to collect soil which was then bagged and returned to the lab for visual examination. Arunin's (1974) trowel scraping method was similar. Soil samples can also be washed through a sieve. If contents of the sieve are submerged, weevils will float to the surface where they can be collected and counted (Tysowsky and Dorsey 1970). Berlese funnels use the heat from light bulbs to dry out soil/litter samples and drive out insects. They are very effective, but unfortunately rather slow. One to three days extracting time are required for typical samples. This means large numbers of funnels are needed to support any sampling program. Extensive banks of these funnels take up considerable space and are rather expensive.

Soil drenching is another approach. Pouring an irritating substance on the soil will drive soil insects to the surface where they can be collected and counted. Pyrethrin solutions have been used in this way for collecting alfalfa weevil adults (Manglitz et al. 1978, Roberts et al. 1979). The disadvantages of this method are that large volumes of liquid are needed (about 4 l/1,860 cm^2), a ten minute period of continuous observation is required for each sample, and some weevils may never surface or be killed by the pyrethrins before they can surface (Tashiro et al. 1983, Harcourt et al. 1983).

Two mark and recapture studies, one using enamel paint and the other P^{32}, have been carried out on the alfalfa weevil. In both cases recapture rates were extremely low and little information was gained (Pamanes and Pienkowski 1965, Manglitz et al. 1978).

Several methods have been developed for sampling alfalfa weevil eggs, however as with adults, none of them are efficient enough to be used for a management-oriented sampling program. Dissecting individual stems for visual examination has been used by several researchers (Woodside et al. 1968, Niemczyk and Flessel 1970, Dively 1970). Pass and VanMeter (1966) developed the so called blender method of egg extraction. Fifteen grams of stem sections 5cm long are put in a blender with water for approximately 10 seconds. The contents are then rinsed through a series of sieves. This process is repeated 5 or 6 times with material from the coarsest sieve. Finally the eggs are separated from the plant debris by flotation in a saturated salt solution. The process is more efficient and recovers more total eggs than hand dissection but viability of the eggs is lower (Townsend and Yendol 1968).

In northern states where most eggs are laid during the spring in green alfalfa stems, oviposition scars can be counted and multiplied by average clutch size for an estimate of egg density (Harcourt et al. 1974). This method does not work for dead stems and is therefore useless for monitoring fall or winter laid eggs. Similarly, a method developed by Simonet and Pienkowski (1977) to clear alfalfa stems and dye insect eggs within them, might also be useful for spring-laid eggs, but it does not work on dead plant material.

MODELS

At least ten computer models have been developed to simulate alfalfa growth, alfalfa weevil development, or the effects of weevil feeding on alfalfa. Some are primarily research tools, others are designed to identify ways to improve alfalfa management. The models are constructed in different ways and vary in degree of complexity depending on their purposes.

The first computer model developed to simulate alfalfa growth was called SIMED (Holt et al. 1975). This model simulates the flow of carbon into and through leaves, stems and roots. It was written in GASP IV, a FORTRAN-based simulation language. Initial validation runs were fairly accurate in spite of the fact SIMED assumes adequate soil moisture and fertility. ALSIM 1, a more complex model, addressed some of

SIMED'S shortcomings. It's updated version (Level 2) contains a soil water budget (Fick 1981). Originally written in CSMP III, the code was also translated into FORTRAN (Onstad and Fick 1981). Input data needed for a simulation run include: a.) amount of leaves, stems, basal buds, and root reserves at the start of the simulation, b.) soil water holding capacity, c.) dates of harvest, d.) latitude, and e.) daily weather data for solar radiation, mean air temperature, and precipitation. The model predicts yield of alfalfa hay, provides growth curves for the various plant parts, and simulates available water in the root zone on a daily basis. One of the model's primary purposes is to aid in studies of management of alfalfa pests.

Complex models such as SIMED and ALFSIM 1 can yield important information on alfalfa management, but they are primarily research tools. Much simpler models have been developed for management-oriented alfalfa yield prediction. The simplest consists of a single equation and requires only the input of degree days (Fick 1984).

The first model to simulate development and population dynamics of the alfalfa weevil was SIMAWEV (Miles et al. 1974). This program was also written in GASP IV. The model assumes an initial adult density, then simulates oviposition, hatch, larval development, pupation, adult emergence, and mortality to each life stage. It is temperature driven, requiring input only of daily maximum and minimum temperatures.

Validation runs indicated the model predicted peaks of the various instars at approximately the right time, but it was not tested for accuracy in predicting adult or egg densities.

Hildebrand (1974) developed the first model which simulated the effect of weevil feeding on alfalfa yield. This model uses optimization techniques to determine what cutting times lead to maximum total yield given the impact of alfalfa weevil feeding and considering the effect on the weevil of B. curculionus parasitization. A similar, but more complicated optimization model was developed by Regev et al. (1976). Here effects of pesticides were included. An interesting conclusion from early runs was that pesticides would be most effective if used against adults in the spring before any damage was evident. This was in spite of the fact that 20% were assumed to survive the treatment.

A third optimization model was developed by Shoemaker (1977). This one examined the weevil control benefits of parasitization by B. curculionus, insecticides, and early harvest. In most cases it predicted early harvest would be the preferred method of weevil control for fields in the Northeast.

Regev's optimization model drew heavily on biological data collected by a team in California led by A.P. Gutierrez. This team put together their own simulation model which simulates plant growth and alfalfa weevil development over a year long period based on early season population estimates and weather data (Gutierrez et al. 1976). Predictions from this model agreed with field samples reasonably well for all life stages except eggs. A reevaluation found that only a small proportion of the eggs in the field were being detected by their sampling of standing green and dried alfalfa stems in the spring. Three quarters of the eggs turned out to be in plant debris on the ground surface (Gutierrez et al. 1976).

Ruesink (1976) developed an alfalfa weevil model which when coupled with SIMED was designed to provide on-line damage forecasts useful immediately to alfalfa growers. Early predictions from the model were good in spite of the fact that initial fall adult populations were guessed at and then adjusted to produce reasonable egg densities.

Recently some of these computer models have been combined or used together to increase the accuracy of their predictions. Shoemaker's original optimization model has been combined with a detailed weevil population dynamics model. The product has been named ALFMAN (Shoemaker and Onstad 1983). ALFMAN has since been combined with ALSIM (Onstad and Shoemaker 1984). The robust strategy predicted by this combination model for conditions in New York was to control weevils solely with an early first harvest.

Computer plant/pest models are useful to growers through their evaluation of management alternatives and predictions, but their main benefit is often to researchers. Models help us understand the overall workings of biological systems and highlight areas where our knowledge is lacking. One such area is the ecology and population dynamics of the overwintering stages of the alfalfa weevil. Existing models have either made gross assumptions about overwintering stages or modeled them but failed to verify their predictions of winter adult and egg densities.

CHAPTER 2: PITFALL TRAPS

EVALUATION OF SIX PITFALL TRAP DESIGNS FOR COLLECTING ALFALFA WEEVIL, *HYPERA POSTICA* (GYLLENHAL), ADULTS DURING FALL AND WINTER

INTRODUCTION

Pitfall traps are widely used as a method for collecting ground-dwelling arthropods (Southwood 1978). There are numerous designs, but all consist of containers buried with their opening level with or just below the soil surface. A killing agent/preservative is usually added to prevent arthropods which fall into the trap from escaping or preying on each other.

Conventional designs are circular, sometimes modified with rain covers (Fichter 1941), funnels (Doane 1961, Houseweart et al. 1979, Wojcik et al. 1972), collars (Epstein and Kulman 1984, Uetz and Unzicker 1976), or time-sort devices (Williams 1958). More recently linear troughs (Pamanes and Pienkowski 1965, Pausch et al. 1979) and barriers (Smith 1976, Reeves 1980) have been used to increase the effective trapping area. Pitfall trap catches depend on both density and activity of the target population. Other factors which influence catches include: trap size (perimeter length), capture efficiency (extent to which a trap actually captures members of the target population which encounter it), retaining efficiency (extent to which members of the target population escape) (Luff 1975), and the attractancy or repellency of baits and killing agents (Greenslade and Greenslade 1971, Luff 1968).

As part of a research program on the behavior of alfalfa weevil adults during fall and winter, an experiment was designed to compare the collection efficiency, installation and servicing effort, and cost of six different pitfall traps.

MATERIALS AND METHODS

The six pitfall trap designs evaluated were: 1.) CIRCULAR. A conventional circular trap, 9.5 cm in diameter, was made from plastic drinking cups similar to the trap used by Morrill (1975). an ethylene glycol solution (automobile anti-freeze) was used as a killing agent. 2.) CIRCULAR WITH RAIN COVER. Identical to the circular trap except that it was equipped with a 20 cm by 20 cm wooden rain cover supported 2.5 cm above the lip of the trap by wooden legs. 3.) BARRIER. This trap consisted of two circular traps set near each other with a vertical aluminum barrier between them. The barrier was 10 cm high with approximately 2.5 cm buried in the soil. The entire trap was 1 m long (Fig. 1). 4.) BARRIERLESS. Two circular traps set with their outside edges 1 m apart as above, but with no barrier between them. 5.) LINEAR. This trap was made as designed by Pausch et al.

(1979) from a 1 m long section of rain gutter. A wooden rain cover 20 cm wide and 104 cm long was supported 2.5 cm above the edge of the trap by wooden legs at the corners. The trap was filled to a depth of approximately 2 cm with ethylene glycol. 6.) DRY LINEAR. Identical to the linear trap above except that no killing agent and no rain cover were used. Small holes were punched in the ends of the trough to let rain water escape.

The experiment was conducted near the middle of a one year old alfalfa field of approximately 10 ha in Bedford Co., Virginia. Five replicates of each type of trap were set 10m apart in a stratified random block design. Barrier, barrierless, linear, and dry linear traps were oriented randomly with respect to compass direction. The traps were operated from mid-November through early January. Every two weeks arthropods in the traps were removed and the killing agent replenished. Samples were returned to the laboratory for sorting and identification.

At the end of the experiment the number of alfalfa weevils and the total number of ground-dwelling arthropods caught in each trap were determined. Overall, 406 alfalfa weevil adults were caught representing 43% of the total catch. No other species occurred frequently enough to warrant individual analysis. Among other arthropods captured were clover leaf weevil, Hypera punctata (Fabricius) (168 or 18%), clover root curculio, Sitona hispidulus (Fabricius) (112 or 12%),

Figure 1. A barrier pitfall trap in operation.

Carabids (69 or 7%), other Coleoptera (72 or 8%), and Spiders (124 or 13%). Trap types were tested for differences in number of target organisms collected with an analysis of variance (Proc ANOVA (SAS 1979)). When significant differences were found, trap types were ranked in order of efficiency with a Duncan's Multiple Range Test (Duncan 1955). Traps were also ranked subjectively for ease of installation and ease of servicing.

RESULTS

Collection efficiencies of the various types of traps were significantly different ($P<0.01$) (Table 1). Barrier traps were the most efficient at collecting alfalfa weevils and also collected the most total arthropods. They were nearly twice as efficient as equivalent traps without barriers. Catches were not significantly different between circular traps and circular traps with rain covers, nor between linear and dry linear traps.

A golf cup hole cutter and a hand trowel were the only tools necessary for installing the circular traps. A heavy-duty circular pizza cutter was used to make a groove in the soil when erecting barriers for the barrier traps. Installation of linear traps required digging a trench with a shovel. Time and effort of installation was least for the

Table 1. Mean number of target arthropods captured per day in six types of pitfall traps.

Type of Trap	Mean/Trap/Day Alfalfa Weevil	Mean/Trap/Day Total Arthropods
Barrier	0.65±0.11a[1]	1.48±0.21a
Linear	0.23±0.05b	0.79±0.04b
Barrierless	0.22±0.05bc	0.32±0.07c
Circular	0.12+0.02bc	0.22±0.08c
Circular with Raincover	0.10±0.03bc	0.28±0.05c
Dry Linear	0.06±0.02c	0.19±0.05c

[1]Mean±SE
Means with the same letter are not significantly different (α=0.05; Duncan's (1955) multuple range test).

circular traps, somewhat more for the barrier traps, and much more for the linear traps (Table 2, column 1).

The circular and barrier type traps were serviced by removing the inner cups and transferring the contents to other containers for transport back to the laboratory. An aquarium dip net was used to remove captured arthropods from the linear traps. Specimens were removed individually with forceps from the dry linear traps. Servicing the circular and barrier traps was easy and quick. Linear traps took somewhat more time and effort, and dry linear traps were still more difficult (Table 2, column 2).

All the materials for the traps were purchased at local grocery and building supply stores. Circular traps and barrier traps required only a few minutes of construction time per trap. Linear traps took about twenty minutes per trap to build as did each rain cover. Costs per trap excluding labor costs are listed in Table 2.

DISCUSSION

Barrier traps clearly outperformed all the other traps in capturing alfalfa weevils and other ground-dwelling athropods. This agrees well with the results of Smith (1976) who trapped in an abandoned tobacco field in Kentucky and Durkis and Reeves (1982) who trapped in a mixed hardwood stand in New Hampshire. Barrier traps are inexpensive and

Table 2. Cost, installation, and servicing effort of six pitfall trap designs.

Type of Trap	Installation Time/Effort	Servicing Time/Effort	Cost Per Trap
Barrier	moderate	low	$.46
Barrierless	low	low	$.16
Linear	high	moderate	$5.13
Circular	low	low	$.08
Circular with Raincover	low	low	$.68
Dry Linear	high	high	$2.73

easy to install and service. Barrier trap design is also very flexible. Traps of many lengths and shapes are possible, and barriers can also be used on sloping ground where linear traps are impractical. In addition, two or more capture points on each side of the barrier or V-shaped barriers allow one to determine whether movement of a target arthropod has a directional component (Smith 1976).

The performance of the linear traps in alfalfa fields during the winter was poorer than reported by Pauch et al. (1980). Retaining efficiency may have been lower once the sides of the trap became dirty. Insects were observed walking on the inside surface of the curved side of the trap, thus avoiding capture, at least temporarily.

Dry linear pitfall traps theoretically allow capture of live specimens, but escape of the target arthropods and predation within the trap are difficult to prevent. Daily servicing would minimize the problem.

Pooled results from all the traps indicate a male to female ratio of 1.8:1 among captured alfalfa weevils. This contrasts with results reported by Miller et al. (1972); they found a 1:2.6 male to female ratio among weevils captured in emergence-type traps during the winter. Two explanations are possible. First there may have been real differences between the sex ratios in the fields in these two studies, though differences of this magnitude seem unlikely. Alternatively males may be proportionally overrepresented in pitfall trap catches and/or females overrepresented in emergence traps. Subsequent absolute density sampling by the author indicated an average sex ratio of 1:1.3 males to females over the next two years at the site of this experiment. This would tend to support the second theory, though the first can not be ruled out.

The choice of a killing agent/preservative must be made carefully when pitfall traps are used. Rate of evaporation, attractancy or repellency to the target species, and toxicity to nearby plants and non-target animals should be considered. Ethylene glycol solutions, such as automobile antifreeze, are recommended for winter use (Steigan 1973), but they are toxic to pets and wild animals which are attracted to their sweet taste. Alternatives which have been used successfully in various situations include: water and detergent (Chiverton 1984), alcohol (Smith 1976), commercial methylated spirit (Greenslade and Greenslade 1971), formalin (Luff 1968), a saturated picric acid solution (Cameron and Butcher 1979), a 1:1 mixture of 70% ethanol and ethylene glycol (Houseweart et al. 1979), a solution of water, ethylene glycol, formalin, and detergent (Morrill 1975), and volatile compounds such as dichlorvos and technical chlorpyrifos crystals (Wojcik et al. 1972).

Alfalfa weevil adults are difficult to collect during fall and winter. Barrier pitfall traps offer an efficient, inexpensive way to do this. The materials necessary to make them are easily obtainable and the time required to install and service them is reasonable. Automobile antifreeze, also readily available, makes a suitable killing agent, but it should not be used where there is a threat to pets or wild animals.

CHAPTER 3: OVERWINTERING ADULTS

OVERWINTERING ECOLOGY OF ALFALFA WEEVIL, *HYPERA POSTICA* (GYLLENHAL), ADULTS: EFFECTS OF FALL MANAGEMENT PRACTICES AT HIGH AND LOW ELEVATIONS IN VIRGINIA

INTRODUCTION

The alfalfa weevil's overwintering habits are somewhat unusual among insects. In the northern part of its range it overwinters as an adult, but in more southerly areas it overwinters in two different life stages: adult and egg. In Virginia, adults aestivate outside the alfalfa fields during the summer then return to the fields during the fall to mate and lay eggs. Introduced biological control agents have largely eliminated the need for insecticidal control of the alfalfa weevil in northern North America, but in the South it is still a major pest and insecticides are heavily relied upon to control it in spite of the presence of these parasites. The area in which this insect retains its major pest status seems to coincide with the part of its range in which both eggs and adults overwinter.

Virginia is a natural laboratory for studying the overwintering ecology of this insect. The climate in the mountainous western part of the state is similar to that of states farther north, while that in the central Piedmont region is similar to more southerly states. This climatic difference corresponds to a difference in average weevil pressure on the first crop of alfalfa. Only about a third of the alfalfa growers in the mountains regularly treat their fields for alfalfa weevil control, while virtually all the growers in the Piedmont region treat on an annual basis (Luna 1981).

Several researchers have hypothesized that adult mortality during migration to and from aestivation sites and over the winter is a key factor in determining year-to-year population levels (Horn 1975, Latheef et al. 1979). Monitoring adult populations in the fall has thus been suggested as a means of predicting potential damage from larval feeding the following spring (Blickenstaff et al. 1972, Schroder and Metterhouse 1980).

Unfortunately there has been no efficient sampling method for accurately measuring adult population densities in their overwintering habitat. A new sampling method, therefore, was developed for this study. It allowed me to make estimates of adult population densities any time during the fall or winter except when the ground was frozen.

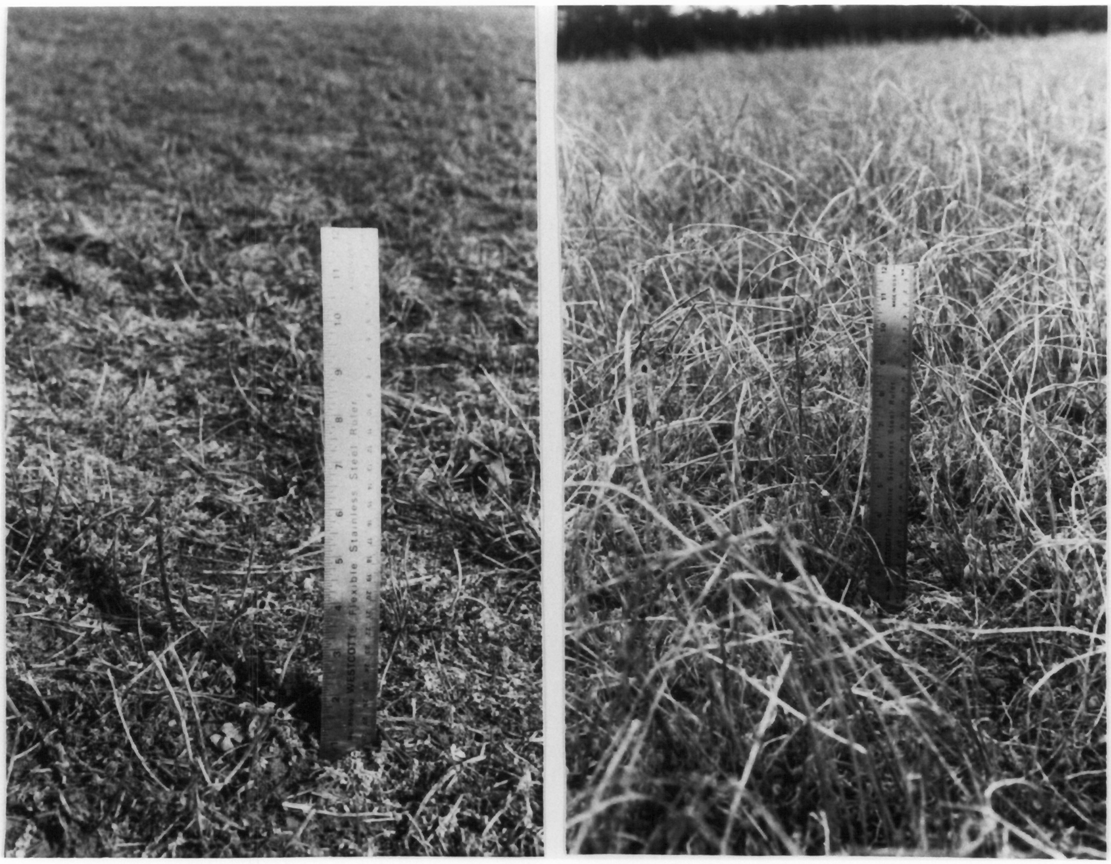
Two study sites were chosen, one in Montgomery County, which is in the western mountains, and the other in Bedford County in the Piedmont region. The sites were at approximately the same latitude (37° 21' N) and only about 105 km apart, but the Montgomery Co. site was at an elevation of 610 m above sea level compared to 300 m at the Bedford Co. site.

A two year study was initiated in the fall of 1983 to examine the overwintering ecology of the alfalfa weevil in commercial alfalfa fields during the fall and winter in these two locations. By better understanding the population dynamics of this insect it was hoped that better management strategies might be developed to help growers cope with their weevil problem and perhaps reduce their dependence on chemical insecticides.

MATERIALS AND METHODS

Sixteen fields, eight in each county, were chosen for the study. The only criterion for selection was willingness of the owner to cooperate. Three different alfalfa varieties were represented and the stands ranged in age from 2-11 years. Stand condition varied from excellent (even and weed-free) to poor (patchy and weedy).

In 1983-84 four of the fields in each county were either harvested or grazed to remove the fall regrowth (Fig. 2b). In the other fields, fall regrowth was left standing and remained through the winter (Fig. 2a) except in two Montgomery county fields which were later winter grazed. The same sixteen fields were studied in 1984-85. Some fields, which received no fall management the year before, were harvested or



A B

Figure 2. A. Fall regrowth allowed to overwinter. B. Stubble following fall regrowth management.

grazed the second year and vice versa. Overall in 1984-85, five out of eight fields in Bedford county received some form of fall management while four out of eight did in Montgomery county (Table 3).

Sweepnet sampling was used to monitor the return migration of adults. In 1983-84, the approximate timing of the start of this migration was determined to be mid-October. In the second year, two fields, one in each county and both unmanaged, were chosen for intensive study and these were sampled at approximately 12 day intervals from mid-October until the alfalfa was frost-killed in mid-November. Four samples of 25 sweeps each were taken along each side of the field at distances of 5, 15, and 30 m from the field edge. Sampling was done in the early afternoon on days when the air temperature was above 16°C and the wind was light. The results were plotted using Surface II (Sampson, 1978).

Population density measurements during and after the migration were made with a newly designed soil/litter sampler (Fig. 3). The Hilburn sampler is similar in appearance to the cylindrical square foot delineating device Hower and Ferguson (1972) used in conjunction with a D-vac. Unlike that device, the Hilburn sampler removes all the plant material, litter and approximately 2 cm of soil in a 1/20 m^2 area. It is made of 3.2 mm thick rolled steel, with 4 solid steel handles each 15 cm long and reinforced at the point of attachment. The pivot point is 7.5 cm long and made of 1.3 cm

Table 3. Physical characteristics of the sixteen fields used in the overwintering population dynamics study.

Field	Var.	Age	Cond.	Crowns/m^2	pH	Fall 83-84	Rgrwth 84-85
Bedford Co.							
Sims	531 Pioneer	2	excel.	183	6.4	no	yes
AW1	?	3	good	127	6.5	no	no
AW2	?	3	fair	70	6.6	no	no
AW3	?	2	excel.	207	6.0	no	no
Carr	Saranac AR	3	good	165	6.2	yes	yes
CW1	531 Pioneer	3	excel.	163	6.6	yes	yes
CW2	Williamsburg	11	poor	73	6.2	yes	no
CW3	531 Pioneer	3	excel.	170	6.5	yes	no
Montgomery Co.							
Airp	Saranac AR	5	good	142	6.5	no	yes
Tunn	Saranac AR	3	excel.	172	6.5	no	no
Chil	?	3	good	193	6.5	no	yes
Styn	?	2	good	318	6.5	no	no
KB1	Saranac AR	2	excel.	163	6.8	yes	no
KB2	Saranac AR	4	good	132	6.7	no	no
KB3	Saranac AR	4	fair	143	6.4	yes	yes
Sale	?	2	good	160	6.3	no	yes

Figure 3. The Hilburn Sampler: A device for measuring absolute densities of adult alfalfa weevils during fall and winter.

thick steel rod. Inside, one section of the bottom of the sampler is inclined downward and its leading edge is a blade of sharpened tool steel. The circular bottom edge of the sampler body also is sharpened.

To operate the Hilburn sampler the operator: 1.) Sets it on the ground pivot point down. Unless the soil is extremely hard or rocky, the weight of the device sinks the pivot point until the blade and bottom edge are in contact with the ground. This immediately cuts off all avenues of escape for insects inside the cylinder. 2.) Next the sampler is turned several full revolutions while downward pressure is applied to the handles until the collecting space inside is full. 3.) Finally, a plastic bag is pulled down over the top of the device and the sampler is inverted to dump the sample into the bag.

Several early prototypes developed in 1982-83 were modified as experience suggested new improvements. Originally there were only two handles, but this led to awkward positions and muscle strain. The pivot point was added to minimize a problem with sideways slipping. Also a bandsaw blade, which was riveted around the bottom edge of the sampler, was removed because it served as a surface for build up of caked-on mud. Other modifications were to enlarge the opening in the bottom, and to remove adjustable depth guides from the outside. Trying to regulate the depth with external guides proved to be unnecessary. Instead the sampler was turned until its inside collecting space was full. By regulating sample volume in this manner, variations in sample depth were kept to acceptable levels.

The Hilburn sampler can not be used when the soil is hard due to drought conditions, or saturated due to recent rains. It is also unusable when the soil is frozen as it was in the study area from mid-December through late-January in 1983-84 and mid-January through mid-February 1985. Each field was sampled four times in 1983-84: late-November, early February, mid-March, and early-April. On each occasion 12 samples were taken per field. Sample sites within the fields were selected in an unbiased manner except that bare spots were not sampled. Due to weather conditions, the shortness of daylight hours during the winter, and lab processing constraints it took from one to two weeks to visit all sixteen fields. Each field required about 1 man-hour to sample. In 1984-85 all sixteen fields were visited twice, once in mid-December and again in late-February. The two fields chosen for intensive study were sampled once a month from October through April except when the ground was frozen. The number of samples per field was increased from 12 to 20 at each visit.

A two-wheeled garden cart was used to transport the samples in the field. Samples were returned to the lab for 48 hrs of extraction time in Berlese funnels. Initially, a bank of 24 funnels was set up, but this was inadequate to cover the needs of ongoing sampling programs so the number was doubled, then eventually increased to 72. Each consisted of two tractor funnels, one inverted over the other. A 60 w light bulb was suspended above the samples which rested on 6.4 mm hardware cloth. Insects were collected in 227 ml canning jars containing alcohol.

Adult weevils were dissected to determine rates of parasitism. Dissections were done using a method modified from Snow (1928). Weevils were partially imbedded in black, molten paraffin. After the paraffin hardened, they were opened under water using microforceps and a dissecting microscope. Parasite larvae were identified using characters described by Fuester (1970) and Thompson (1954).

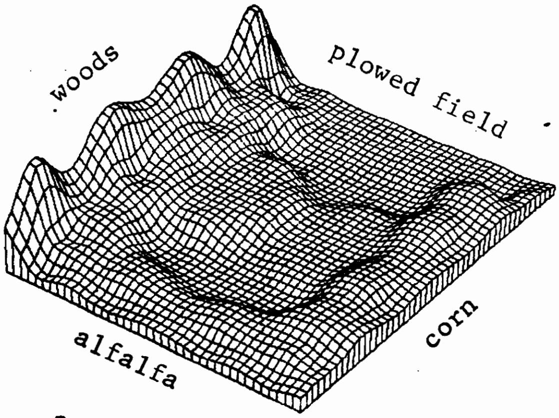
Other measurements taken once a winter in each field were soil pH, soil fertility, stubble height, and crown density (Table 3). The latter was recorded while taking absolute density samples with the Hilburn sampler. The severed taproots are readily observable and easily counted.

Proc FUNCAT, a SAS procedure (SAS 1979) which estimates minimum chi-square values, was used to analyze the population density data. Non-parametric statistical methods were chosen as the best way to deal with the unbalanced design of the experiment, caused by unanticipated action by the growers, and the non-normally distributed data which included many zeros. Tests were made to detect management, county, and date effects as well as interactions.

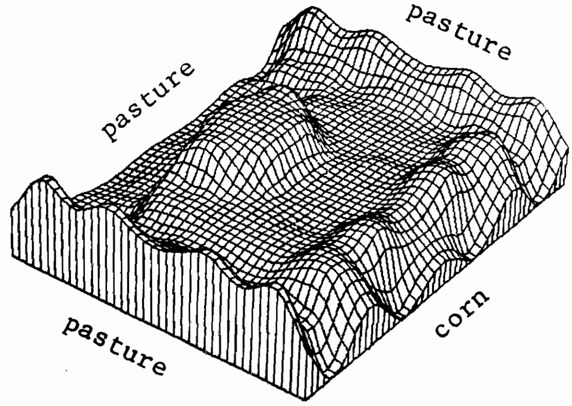
RESULTS

In the mountains of southwest Virginia, the fall migration of alfalfa weevils began in mid-October with peak populations reached in mid-November. At lower elevations the migration was slightly delayed with peak densities occurring in early December. The weevils distribute themselves rather quickly and evenly throughout the fields. Figure 4 illustrates the pattern of their distribution in the two intensively studied fields during the period of mid-October through mid-November, 1984. The relative numbers in each map do not reflect population densities because sampling was done with a sweepnet. There is evidence of higher population densities early in the migration along the side of the Bedford, Co. field bordered by woods (Fig. 4A). Populations were high around three sides of the Montgomery Co. field on the first sampling date. This field was surrounded by agricultural land and the nearest woods were 50 m away from the field borders.

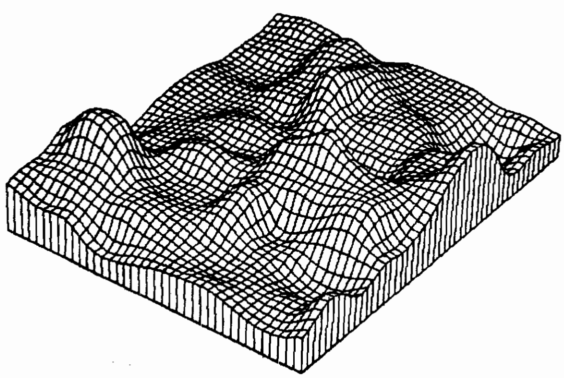
In 1983-84 adult population densities in the late fall averaged $11.0/m^2$. About half of them survived the coldest part of the winter. Additional mortality reduced the average number present to less than $3.8/m^2$ by early April (Fig. 5). The following year an average of $5.7/m^2$ were present in December, but only $2.2/m^2$ survived until February. Population densities in the intensive study fields reached a peak of $16/m^2$ in Montgomery county on November 14, 1984 while the



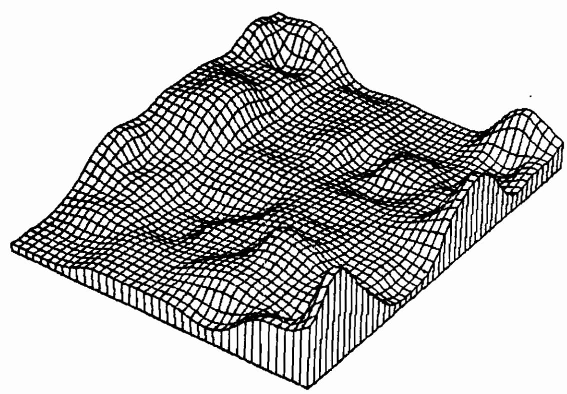
A Sims Field, Oct. 17, 1984



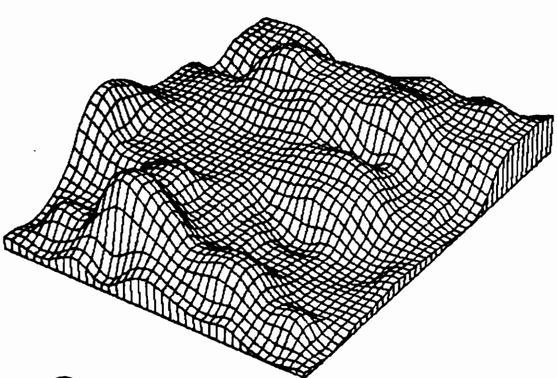
D Sale Field, Oct. 19, 1984



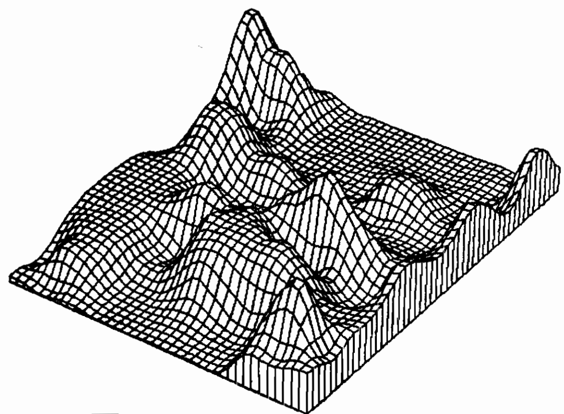
B Sims Field, Oct. 31, 1984



E Sale Field, Nov. 9, 1984



C Sims Field, Nov. 11, 1984



F Sale Field, Nov. 15, 1984

Fig. 4. Distribution of alfalfa weevils in the intensive study fields during the fall of 1984. A-C Sims Field, Bedford Co., D-F Sale Field, Montgomery Co.

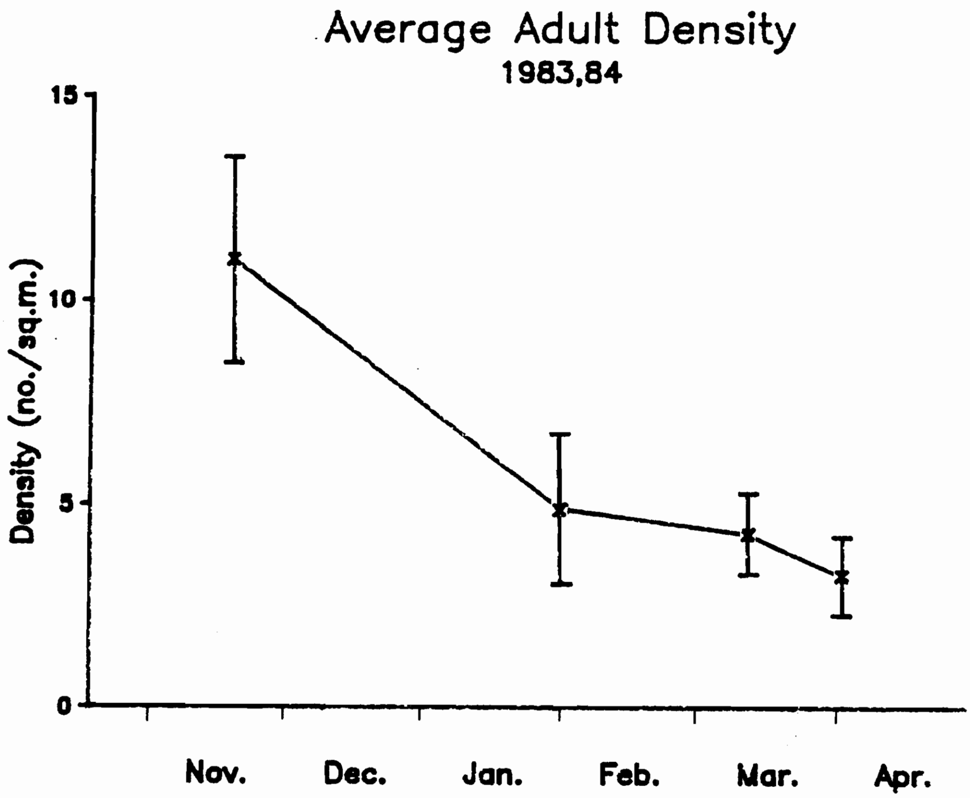


Fig. 5. Average population density of overwintering alfalfa weevils in sixteen commercial alfalfa fields in 1983-84. Mean/m^2 ± SE.

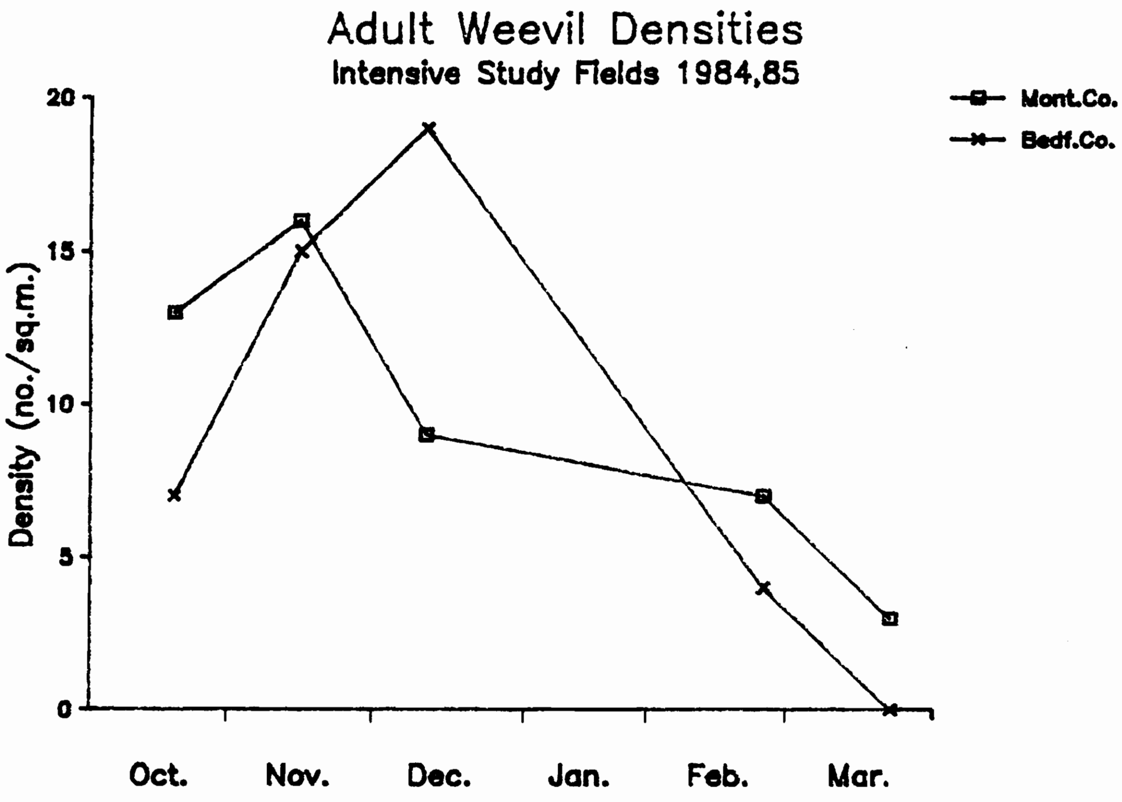


Fig. 6. Population densities of alfalfa weevils in the intensive study fields 1984-85.

Bedford county field did not reach its peak of $19/m^2$ until December 10 (Fig. 6).

Comparison of fields by county indicated no significant differences in overwintering population densities in either 1983-84 or 1984-85 (Tables 4 and 5). There were also no significant county-date interactions in either season. In 1983-84 the first sampling period measured significantly higher populations than the following periods, but this was the only statistically significant date effect detected.

The effect of fall management was highly significant both years (df=1, χ^2=40.69, P<0.0001 in 1983-84 and df=1, χ^2= 9.05, P<0.003 in 1984-85). In unmanaged fields the average density over the entire 1983-84 season was $9.42\pm1.84(SE)/m^2$ in a total sample area of 19.2 m^2. This compares to $3.42\pm0.69/m^2$ in 22.8 m^2 in fields receiving some form of fall or winter management. The corresponding densities for 1984-85 were $5.36\pm1.33/m^2$ in 14.0 m^2 in unmanaged fields and $2.33\pm0.40/m^2$ in 18.0 m^2 in managed fields. The average number of overwintering weevils was higher in unmanaged fields during most of the 1983-84 season (Fig. 7).

No consistent correlations between weevil populations and field characters such as variety, stand condition, soil fertility, or crown density were observed. Proximity to wooded or uncultivated areas which might offer suitable shelter during aestivation also seemed to have no relation to eventual overwintering populations.

Table 4. Adult alfalfa weevil population densities in managed and unmanaged alfalfa fields in Bedford and Montgomery counties in 1983-84.

	Late Nov.	Early Feb.	Mid March	Early Apr.
Bedford Co.				
unmanaged	6.25±1.65*	12.08±6.32	10.00±0.68	5.42±1.85
managed	6.67±1.36	2.08±1.25	2.92±1.05	2.08±1.58
Montgomery Co.				
unmanaged	20.42±7.86	5.83±0.83	1.67±1.67	6.67±5.00
managed	10.83±3.69	1.67±0.74	2.22±1.11	1.39±1.09

*Mean/m²±SE

Table 5. Adult alfalfa weevil population densities in managed and unmanaged alfalfa fields in Bedford and Montgomery counties in 1984-85.

	Mid December	Late February
Bedford Co.		
unmanaged	11.67+3.84*	2.67+0.67
managed	2.60+0.93	1.60+0.68
Montgomery Co.		
unmanaged	5.00+1.96	3.00+1.35
managed	3.50+0.65	1.75+0.85

*Mean/m^2+SE

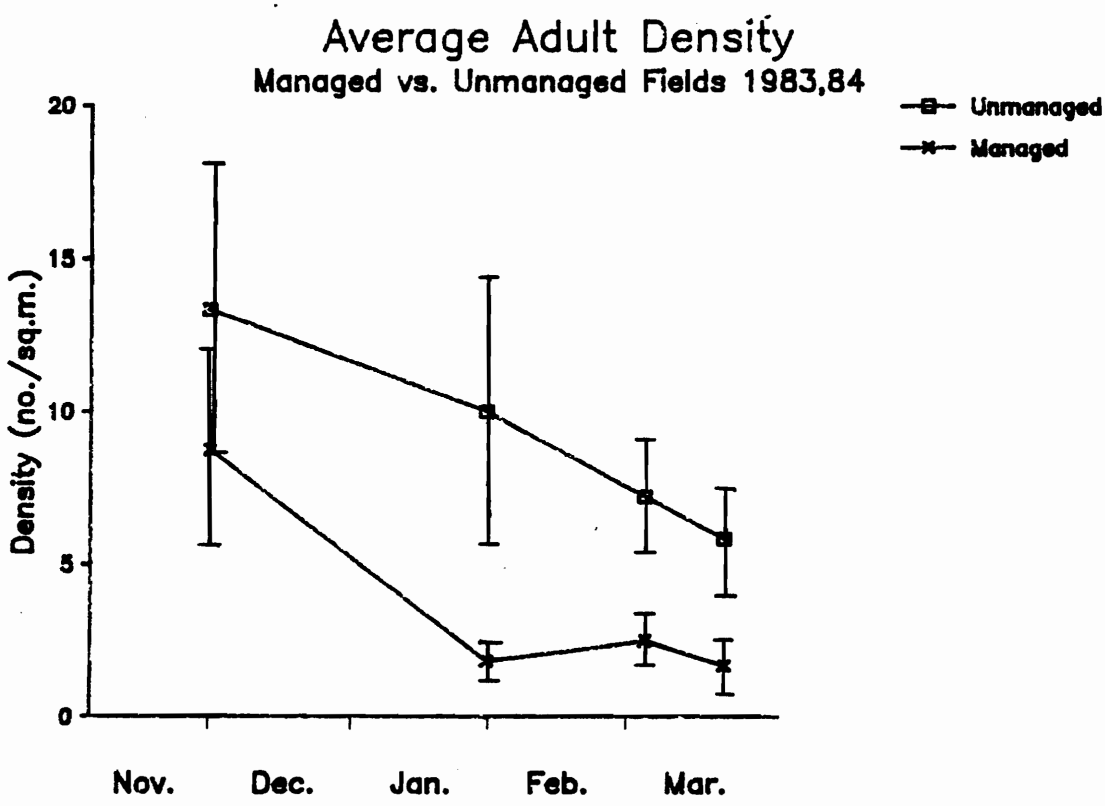


Fig. 7. Average population density of overwintering alfalfa weevils in managed and unmanaged fields in 1983-84. Mean/m^2 ± SE.

A variety of other arthropods, especially beetles and some spiders, also overwinter as adults in alfalfa fields. The clover root curculio, Sitona hispidulus (Fabricius), is especially abundant. In 1983-84 they outnumbered alfalfa weevils 2.8:1 in the absolute density samples. A total of 620 were collected in 768 samples. The following season they were relatively less abundant (218 in 640 samples), but still outnumbered alfalfa weevils 1.8:1. Population densities of this species also seem to be affected by fall management practices, but to a lesser degree. No significant differences between managed and unmanaged fields were found in 1983-84, but the following year significantly more were found in unmanaged fields (df=1, χ^2=4.01, P<0.045). A highly significant county difference also was noted in that year. Montgomery county fields supported much higher clover root curculio populations (df=1, χ^2=28.00, P<0.0001)

Arthropod predators of a size large enough to feed on adult alfalfa weevils are rare in this environment. Carabid beetles and spiders turn up frequently in absolute density samples, but most of the species are about the same size or smaller than the adult weevils. In both years carabids were significantly more abundant in Montgomery Co. (df=1, χ^2=5.41, P<0.02, χ^2=11.32, P<0.0008) and in 1983-84 more were found in managed fields (df=1, χ^2=18.44, P<0.0001). This management effect was not observed the following season. Spiders populations were similar in the two counties both years, but in 1984-85 significantly more were caught in unmanaged fields ($df=1$, $\chi^2=8.15$, $P<0.0043$)

The majority of the other insects extracted from the absolute density samples were beetles. Staphylinids, lathridiids, chrysomelids, coccinellids, and scarabaeids were among the most common. Members of these families and all other adult beetles, excluding alfalfa weevil, clover root curculio, and carabids, were pooled into a group called other Coleoptera. This group was most abundant in the early season samples and in 1983-84 they were significantly more abundant in Montgomery Co. ($df=1$, $\chi^2=10.16$, $P<0.002$). The trend was reversed in 1984-85; Bedford Co. fields had higher populations. Managed fields seemed to support more of these beetles in 1983-84 ($df=1$, $\chi^2=10.73$, $P<0.002$), but not in 1984-85.

Larval stages of three parasites were found in dissected adults. The most common was _Hyalomyodes triangulifer_ (Loew), a native Tachinid. Less common were two Braconids introduced to this country as biological control agents, _Microctonus aetheopoides_ Loan, and _M. colesi_ Drea. The proportion of weevils which were parasitized was generally less than 10%, though it did reach 16.1% in Bedford Co. in 1984-85. Over three quarters (78.7%) of all the parasites recovered during the study were _H. triangulifer_ (Table 6).

Table 6. Parasitization rates of adult alfalfa weevils between 1982 and 1985 in Bedford and Montgomery counties.

	1982-83	1983-84	1984-85
Bedford Co.			
no. dissected	938	143	93
H. triangulifer	73 (7.8%)	4 (2.8%)	12 (12.9%)
M. aetheopoides	11 (1.2%)	2 (1.4%)	3 (3.2%)
M. colesi	2 (0.2%)	4 (2.8%)	0 (0.0%)
Total	86 (9.2%)	10 (7.0%)	15 (16.1%)
Montgomery Co.			
no. dissected	101	115	113
H. triangulifer	2 (2.0%)	1 (0.9%)	8 (7.1%)
M. aetheopoides	2 (2.0%)	1 (0.9%)	1 (0.9%)
M. colesi	1 (1.0%)	0 (0.0%)	0 (0.0%)
Total	5 (5.0%)	2 (1.7%)	9 (8.0%)

DISCUSSION

The difficulty of sampling alfalfa weevil adults in the fall and winter has retarded not only our knowledge of its overwintering ecology but also severely limited meaningful evaluation of alfalfa management practices which might be beneficial as weevil control measures through their impact on adults. The Hilburn sampler was developed in response to this problem and it allowed me to make estimates of population densities in their overwintering habitat.

Unlike sweepnets, pitfall traps, emergence-type traps, and other relative sampling methods, catches with this device are not dependent on weevil activity levels. As long as the ground isn't too dry, too wet, or frozen, the Hilburn sampler can be used at any time of day, and in most weather conditions. In the field, this sampler may be quicker and probably more accurate than other methods involving D-vacs, soil drenches, or soil removal used alone or in various combinations. Tests of capture efficiency in which a sample of the next 2cm of soil was taken immediately after the regular sample indicated no detectable loss of target insects during sampling. As a test of reliability Southwood's (1978) formula for determining sample size in a homogeneous habitat: $n=(s/E\bar{x})^2$ where n=number of samples, s=standard deviation, $\bar{x}$=mean, and E=standard error as a decimal of the mean, was solved for E using the fixed sample sizes in this study. Over the range of densities present, E varied from 0.25-0.40. To obtain E=0.10, sample sizes of between 300 and 1225 would be required. This range is equal to or lower than values reported for other sampling methods at equivalent weevil densities (Guppy and Harcourt 1977, Roberts et al. 1982, Harcourt et al. 1983).

An individual of average physical strength using the Hilburn sampler can take about one hundred samples in a day. Since each sample must be processed for 48 hrs in a Berlese funnel, lab processing constraints, rather than field time, quickly limit the scope of any sampling program. For this reason, the Hilburn sampler is strictly a research tool. A second factor making it unsuitable for widespread use as a monitoring device is that it cuts off the crowns and thus kills the alfalfa plants in the area sampled. A regular monitoring program through season after season would contribute to the thinning and decline of an alfalfa stand. Nevertheless, I feel this device is an important tool which has already helped us learn much about the population dynamics of the alfalfa weevil and associated arthropods. For the first time the alfalfa management technique of removing fall regrowth has been directly evaluated as a weevil control tactic by measuring its effect on adult population densities.

Removal of fall regrowth via a late fall harvest or winter grazing is already practiced by some Virginia growers. Alfalfa given a recovery period of about six weeks to replenish its root reserves, can be safely harvested or grazed once the tops are frost-killed and the crowns are dormant (Sholar et al. 1982, 1983, Collins and Taylor 1980). Not only does this practice increase yield with a late fall harvest of reasonably high quality hay (Collins and Taylor 1984, Dexter 1964), it also helps reduce adult alfalfa weevil populations.

My data suggest that fewer migrating weevils are attracted to fields devoid of fall regrowth and fewer survive the winter in these fields. In contrast, weevils in unmanaged fields survive in greater numbers and potentially produce many more offspring with a corresponding increase in damage to the spring crop. The microenvironment in these fields is moderated by the presence of an insulating layer of air trapped in a mat of plant material. Properly timed removal of fall regrowth, therefore, should more than pay for the cost of removal both in additional alfalfa yield and in reduced or delayed weevil pressure the following spring.

The Hilburn sampler would be useful for evaluating the weevil control potential of other management options such as late winter flaming to burn off the dead plant material and fall insecticide applications aimed at returning adults. Perhaps a more important use, though, would be to calibrate a much needed, but as yet undeveloped, monitoring method for adults that would be quick and easy, and thus suitable for pest management programs.

Alfalfa fields in Bedford Co. have a history of annual spring insecticide applications to control alfalfa weevil larvae. This may explain the greater abundance of several non-target arthropod groups in the Montgomery Co. fields, many of which do not have a history of regular insecticide use. Los (1982) reported similar results for non-target arthropods captured in the summer in treated and untreated alfalfa fields. Surprisingly, though, rates of parasitization were not higher in Montgomery Co.. Parasites of adult weevils are apparently of limited importance in this area. The most effective, _H_. _triangulifer_, is a native parasite with at least eight other known beetle hosts (Thompson 1954, Wellso and Hoxie 1969). This apparent paucity of natural enemies in the weevil's overwintering habitat increases the importance of finding management practices which will help control this pest.

CHAPTER 4: OVERWINTERING EGGS

IMPORTANCE OF OVERWINTERING EGGS OF THE ALFALFA WEEVIL, *HYPERA POSTICA* (GYLLENHAL), IN VIRGINIA

INTRODUCTION

In North America the alfalfa weevil overwinters as an adult in the northern part of its range, where winters are relatively harsh. Introduced parasites have largely brought this pest under successful biological control over most of this area (Day 1981). In the southern United States, in spite of the presence of these parasites, the alfalfa weevil remains a serious pest. This difference is related to the successful overwintering of eggs. Where winters are mild, fall-laid eggs as well as adults are able to survive winter temperatures.

The biology of the alfalfa weevil in Virginia is reviewed by Evans (1959). Newly emerged adults, still reproductively immature, leave alfalfa fields to aestivate in fence rows and wooded areas. They return in the fall to complete their sexual development, mate, and lay eggs. Adult activity continues during the winter whenever temperatures are favorable. Mating can take place at temperatures as low as 7°C and oviposition has been observed at 1.7°C (Day 1971). The eggs are deposited in living or dead alfalfa stems, weed stems, or plant debris on the soil surface. In the laboratory it has been shown that oviposition is initiated within 72 hrs after mating (LeCato and Pienkowski 1972). In a laboratory environment the fecundity of this insect is truly remarkable. A single female can produce up to 100 eggs/day and over 6400 in a lifetime (Coles and Day 1977). In nature the eggs may incubate for as little as four days if they are laid in warm weather or as long as five months if they are laid in the fall (Manglitz and App 1957).

A correlation has been shown to exist between overwintering eggs and early spring larval populations (Armbrust et al. 1966). This is important because alfalfa in an early growth stage is less tolerant of weevil feeding. Damage is most severe when large numbers of larvae attack plants early in the spring when they are still very small.

A three year study was initiated in 1982 to determine the importance of overwintering eggs in Virginia. Two study sites were chosen, one in Montgomery county in the western mountains, the other in Bedford county in the central peidmont region. Though the sites were only 105 km apart and at approximately the same latitude (37° 21' N), they differed in elevation, severity of winter weather, and historical weevil pressure. The Montgomery Co. site at 610 m above sea level has a relatively harsh winter and historically low weevil pressure, while in Bedford Co., elevation 300 m, winters are milder and weevil pressure is usually high.

MATERIALS AND METHODS

Eight commercial alfalfa fields in Bedford Co. and an equal number in Montgomery Co. were used in this study. In 1983-84 four of the fields in each county received some form of management which removed fall regrowth leaving only short stubble during the winter. Two of the unmanaged fields in Montgomery Co. were later grazed during the winter which also removed fall regrowth. In 1984-85 the same fields were studied, but some fields in which fall regrowth was removed the year before were left unmanaged and vice versa. Overall in the second year five fields in Bedford Co. and four in Montgomery Co. were managed to remove fall regrowth.

From the start of the fall migration in mid-October until the alfalfa tops were killed by frost, adult weevils were collected by sweeping with a standard 38 cm sweepnet. Later in the season pitfall traps (see Chap. 2) and a newly designed absolute density sampler (see Chap. 3) were used for collecting adults.

Females were dissected and their stage of reproductive development categorized using methods modified from Snow (1928) and Tombes (1964). Weevils were embedded dorsal side up in black paraffin in a dissecting dish. They were dissected under water using microforceps and a microscope.

Sampling for overwintering eggs has traditionally been done either by splitting individual stems with a razor blade or breaking the stems up in a blender then separating the eggs from plant debris by flotation (Pass and Van Meter 1966). Both methods are labor intensive and require additional tests to determine what proportion of the eggs are viable. Less labor intensive estimates of overwintering egg populations can be made by collecting plant material and litter in the field and incubating it indoors (Woodside et al. 1968). Viable eggs in the samples will hatch and the larvae can be counted.

Samples of this type were taken in each field once in early February after the coldest part of the winter and again in late March just as the first larvae were hatching. The sampling procedure was as follows: an L-shaped piece of wire 33.3 cm on a side was used to delineate 1/9 m^2 areas for each sample. Hedge clippers were then used to sever all standing plant stems at ground level. Finally all plant material in the sample area, including debris on the soil surface was transferred to a 3.8 litter cylindrical, cardboard food carton. Nine samples per field were taken at each visit.

In the greenhouse a small container of water with a wick of rolled paper toweling was added to each carton to maintain high humidity, a requirement for egg hatch in the laboratory

(Koehler and Gyrisco 1961). The regular cardboard top of each carton was replaced with a piece of translucent polyethylene held in place with a rubber band. A thin layer of a sticky material (Tanglefoot™) on the underside of the plastic served to trap first instars which crawled up the sides of the carton toward light entering from above.

Temperature in the greenhouse was regulated between 13° and 29°C. After four weeks the plastic was removed and larvae counted. Nearly all larvae in the mid-winter samples were found on the underside of the plastic in the sticky material. The system was less successful with the late winter samples. Many of these larvae showed no positive phototaxis, instead remaining with the plant material in the bottom of the carton. The presence of some green shoots among the plant material may have been responsible for this change in behavior. A series of sieves with mesh openings of 1.4 mm, 1 mm, and 0.25 mm was used to separate the insects from the plant material so they could be counted.

Egg density data were analyzed for county, and management effects using PROC GLM, a SAS procedure which tests general linear models (SAS 1979).

RESULTS

Dissection of female weevils indicated most were sexually mature shortly after they reappeared from their aestivation sites. A preliminary study using weevils captured in pitfall traps between November 18 and December 2, 1982 in Bedford Co. indicated that 89.5% already had fully developed ovaries and contained full-size eggs in their oviducts. In fact, of 147 unparasitized females caught between November 18, 1982 and January 13, 1983 only 3 (2%) had ovaries which were not fully developed.

In the following seasons females from both Bedford and Montgomery counties were dissected. Absolute density samples during these years indicated a male to female sex ratio of 1:1.05. By late November, 1983 100% of the unparasitized females in Bedford Co. had fully developed ovaries and 69.8% contained full-size eggs. At the same time in Montgomery Co., 96.8% had fully developed ovaries and 61.3% contained eggs. During the remainder of the 1983-84 season all unparasitized females captured through early April in both locations had fully developed ovaries and only 3 (5%) found in February did not contain full-size eggs in their oviducts.

In 1984-85 sampling in two fields chosen for intensive study began on October 17. At that time 66.7% of the females in Bedford already contained full-size eggs. In contrast, only 50.0% of the females in Montgomery Co. had fully developed ovaries. After October 31, however, all unparasitized females from both counties had fully developed ovaries and by December 10 virtually all contained full-size eggs.

Counts of larvae hatched from field collected plant material samples showed no significant differences between counties in early February, but Bedford Co. fields had higher populations in both years by late March (Tables 7 and 8). In Bedford Co. unmanaged fields also had significantly more viable eggs than managed fields on both sampling periods in 1984. This trend was not evident in 1985. Montgomery Co. fields showed no management effect in either year. In both locations in 1984, relatively large numbers of viable eggs were present in early February indicating many fall-laid eggs survived the coldest part of the winter. In contrast, the data from 1985 indicate almost no survival of fall-laid eggs in either county.

DISCUSSION

Fall oviposition was documented by Parks (1914) in Utah shortly after the alfalfa weevil was introduced to this country. He also reported that few if any of these eggs survive until the following spring. Similar reports have been published from Michigan, Wisconsin, and Pennsylvania (Casagrande and Stehr 1973, Litsinger and Apple 1973, Townsend and Yendol 1968). In contrast, researchers in Alabama, South Carolina, and Tennessee report fall-laid eggs are very important to the population dynamics of this insect in their areas (Bass 1967, Tombes 1964, Bennet and Thomas

Table 7. Alfalfa weevil egg densities in managed and unmanaged fields in 1984.

	Fall Management	Early February		Late March	
Bedford Co.	no	282+87[1] a	x	928+154a	x
	yes	57+7 b		474+35 b	
Montgomery Co.	no	74+9 a	x	110+79 a	y
	yes	75+25 a		144+49 a	

[1] Mean/m² +SE

Means for a given county and date with the same letter are not significantly different at α=.05.

Table 8. Alfalfa weevil egg densities in managed and unmanaged fields in 1985.

	Fall Management	Early February		Late March	
Bedford Co.	no	5+2[1] a	x	198+19 a	x
	yes	2+2 a		307+58 a	
Montgomery Co.	no	1+1 a	x	81+31 a	y
	yes	1+1 a		86+13 a	

[1]Mean/m²+SE
Means for a given county and date with the same letter are not significantly different at α=.05.

1964). An intermediate situation occurs in Ohio, Illinois, and Indiana. The importance of overwintering eggs varies depending on location within these states (Niemczyk and Flessel 1970, Hsieh and Armbrust 1974, Hintz et al. 1976). Virginia also falls in this category. Woodside et al. (1968) documented that there is more fall and winter oviposition at lower elevations within Virginia and we now also know that females are reproductively mature sooner in these areas. Oviposition in late winter, after the coldest temperatures have occurred, is also heavier at lower elevations and may be as important as fall-laid eggs in contributing to early spring larval populations.

This geographic spectrum of importance of overwintering eggs can be shifted by unusual winter weather. In Virginia the 1984-85 winter season was mild through early January, but record cold temperatures were recorded a few weeks later (-28°C in Blacksburg and -23°C in Bedford on January 21) (NOAA 1985, Appendix B). Very few fall-laid eggs survived these conditions even at low elevations. As a consequence weevil pressure on the crop was light throughout the state that spring.

In milder winters overwintering eggs which survive are further along in their development than their spring-laid counterparts. For this reason they hatch and begin feeding on alfalfa at an early and very vulnerable growth stage.

Alfalfa management techniques can be used to decrease survival of overwintering eggs. Fall harvest and winter grazing remove fall regrowth and leave only short stubble to overwinter. Not only does this physically remove some eggs, it should also limit suitable oviposition sites and expose both adults and eggs to more extreme temperatures. By thus increasing mortality among overwintering eggs, these techniques should delay peak weevil pressure on the crop. Though this may not in itself provide adequate control in heavily infested areas, it should be an important component in any integrated control program.

CHAPTER 5: SIMULATION MODEL: OAWSIM

OAWSIM: A MODEL SIMULATING POPULATION DYNAMICS OF OVERWINTERING LIFE STAGES OF THE ALFALFA WEEVIL, HYPERA POSTICA (GYLLENHAL)

INTRODUCTION

The alfalfa weevil is a pest of alfalfa, but its importance varies within its range. In northeast North America introduced biological control agents have reduced the status of this insect to a minor pest (Day 1981). Though the same parasites are established in the South, the alfalfa weevil remains a major pest capable of inflicting heavy damage to alfalfa. Several factors related to survival of the overwintering stages (adults and eggs) may be responsible for this difference. The region in which this insect retains its major pest status seems to coincide with areas having mild winters. Under these conditions, large numbers of eggs are laid during fall and winter and many survive. These eggs hatch early in the spring and attack the alfalfa at an early and very vulnerable growth stage.

A simulation model named OAWSIM for Overwintering Alfalfa Weevil Simulation, was developed as a tool for studying the population dynamics of this insect during fall and winter. The model relates oviposition and mortality of both eggs and adults to temperature. It also accounts for the effects of parasites and management practices which alter the microenvironment in the weevil's habitat. OAWSIM has been used to test the following hypotheses: 1.) Parasites of adult weevils are important population regulators. 2.) Removal of fall regrowth decreases overwintering populations. 3.) Regional differences in weevil impact in Virginia are related to climatic differences which influence survival of overwintering eggs and/or adults.

METHODS

Code for OAWSIM was written in FORTRAN (see appendix) and the program was run on an IBM PC using the IBM FORTRAN Compiler. The model consists of eight parts, a main program and seven subroutines.

Subroutine INPUT:

This subroutine prompts the user to enter initial values for controlled inputs: 1.) adult weevil population density (number/m^2), 2.) adult parasitization rate (%), 3.) fall regrowth management practices used (none, harvest, graze, burn), 4.) date of the regrowth management, 5.) direct mortality levels attributable to regrowth management, and 6.) location and year of temperature records to be used in the simulation. For each run the initial values chosen are sent to an output file and printed at the top of the simulation results.

Subroutine TEMP:

Max-min air temperatures for the simulation period (November 1 to March 31) are read in from previously created data files. Data from National Oceanic and Atmospheric Administration stations in Bedford (Bedford Co.) and Blacksburg (Montgomery Co.) in 1983-84 and 1984-85 were used for validation runs (Appendix B).

Max-min air temperatures are converted to estimates of soil surface temperatures and corrected for the presence or absence of fall regrowth according to the following formulae derived from experiments on bare soil and sod (Baker 1965). When fall regrowth is left standing to overwinter, its presence will be assumed to insulate the soil and elevate low temperature readings by 3°C. Under these conditions, the high temperature at the soil surface is assumed to be equal to the daily maximum air temperature. Fields harvested, grazed, or burned to remove fall regrowth have greatly reduced amounts of plant material to insulate the soil. Temperatures at the soil surface approximate air temperatures at night, but during the day high temperatures are assumed to be elevated 3°C.

Subroutine CALC:

Calculations in this subroutine are contained in three loops. Within the inner loop a sine wave function is fitted to the corrected max-min temperature data and instantaneous temperatures are estimated from this curve ten times each twenty four hours. With each cycle the affects of the average temperature for that 0.1 day period on the insect are calculated and used to update conditions in the simulated weevil population. The equations which adjust adult and egg densities are contained in the nested subroutines AWMORT, OVIPOS, and EGGMORT.

The intermediate loop cycles once a day and calls subroutine PRINT which records the density of adults and viable eggs as well as the Julian Date at the beginning of each day. Direct mortality from regrowth management practices is simulated on the specific date chosen by the user. After any form of regrowth management the field begins to experience soil surface temperatures according to the uninsulated formula.

The outer loop cycles once a month and sends values for Julian day, adult density, and egg density to the screen so the user can follow the progress of the simulation as the calculations are being done.

Subroutine AWMORT:

Soil surface temperatures below -10°C are assumed to cause mortality to adults. The longer the temperature stays below this threshold, the more weevils are killed. An equation describing this relationship was derived from data presented by Peterson (1960).

$$M=9.91+0.988x$$

M=percent mortality
x=time below -10°C in days.
$r^2=0.95$

Subroutine OVIPOS:

After correcting for parasitized individuals, this subroutine calculates the number of eggs laid by females at the estimated temperature. The threshold for oviposition in the field (1°C) and the equation relating oviposition to temperature are taken from Hintz (1972).

$$E=-23.03+0.7017x$$

E=number of eggs laid/female/day
x=temperature in °F.

Subroutine EGGMORT:

Egg mortality from cold temperatures is assumed to occur whenever the temperature drops below -6°C. An equation describing this relationship was derived from data presented in Shade and Hintz (1983).

$$M=3.77+1.83x$$

M=percent mortality to eggs
x=time below -6°C in days.
$r^2=0.92$

Subroutine PRINT:

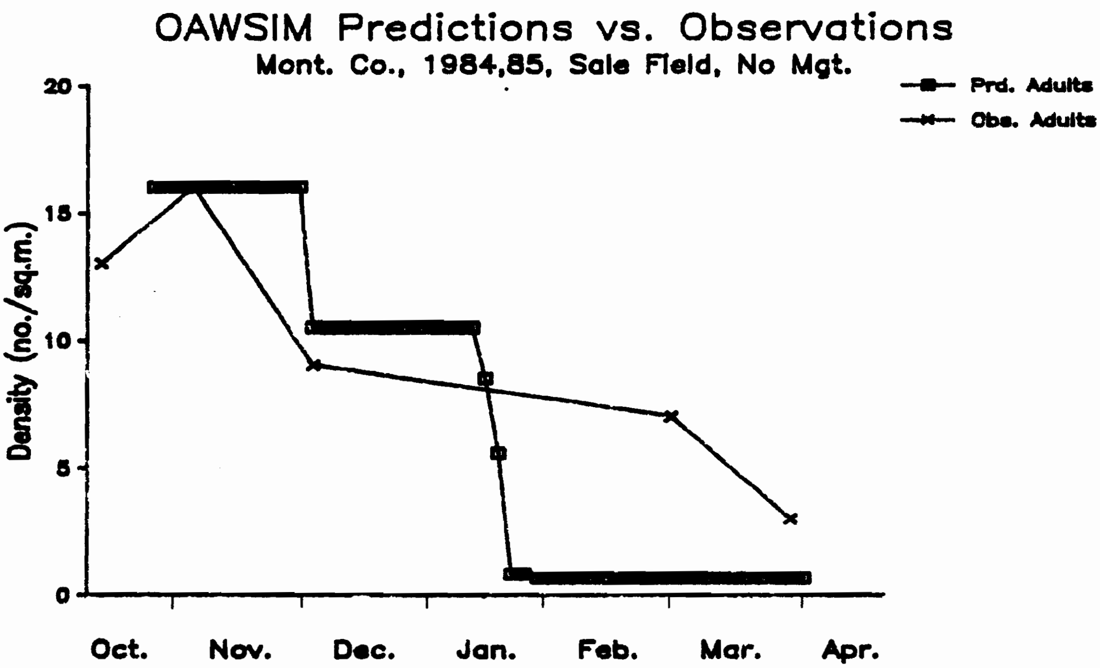
This subroutine produces a table of results for each simulation run. At the top it gives the values chosen by the user for controlled inputs. Following this, there is a listing of daily adult and egg densities in numbers per square meter. Also listed are the Julian Day and maximum and minimum air temperatures.

RESULTS

The model was validated against field measurements of both adult and egg densities taken in sixteen commercial alfalfa fields between 1983 and 1985. Predictions from the model are compared to field data from four representative fields in Figures 8-11.

Simulation runs designed to test the importance of adult parasites demonstrated that at the low rates typical in Virginia they have little effect on the number of eggs which overwinter successfully. Parasitization rate in the model is directly related in an inverse manner to the number of viable eggs at season's end. With other parameters held constant, a 5% increase in parasitization results in a 5% decrease in viable eggs.

An evaluation of regrowth management strategies indicates that any form of management which removes fall regrowth dramatically reduces overwintering eggs. A comparison of man-



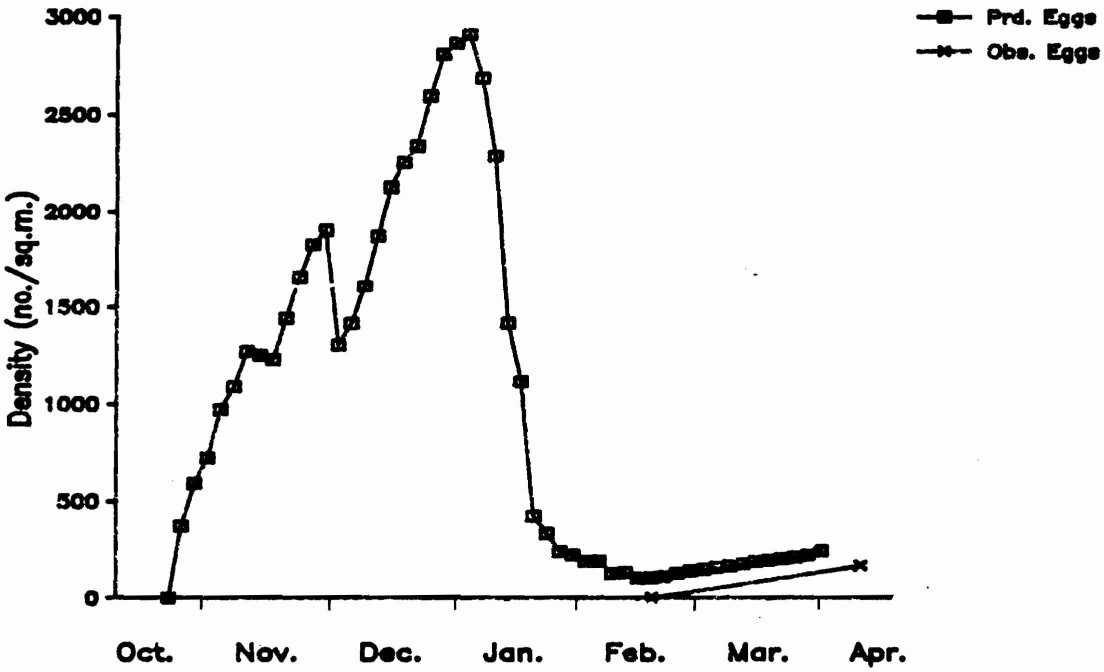


Fig. 8. Comparison of OAWSIM predictions and field measurements of alfalfa weevil adult and egg densities in Montgomery Co., 1984-85, Sale field. The field received no fall regrowth management.

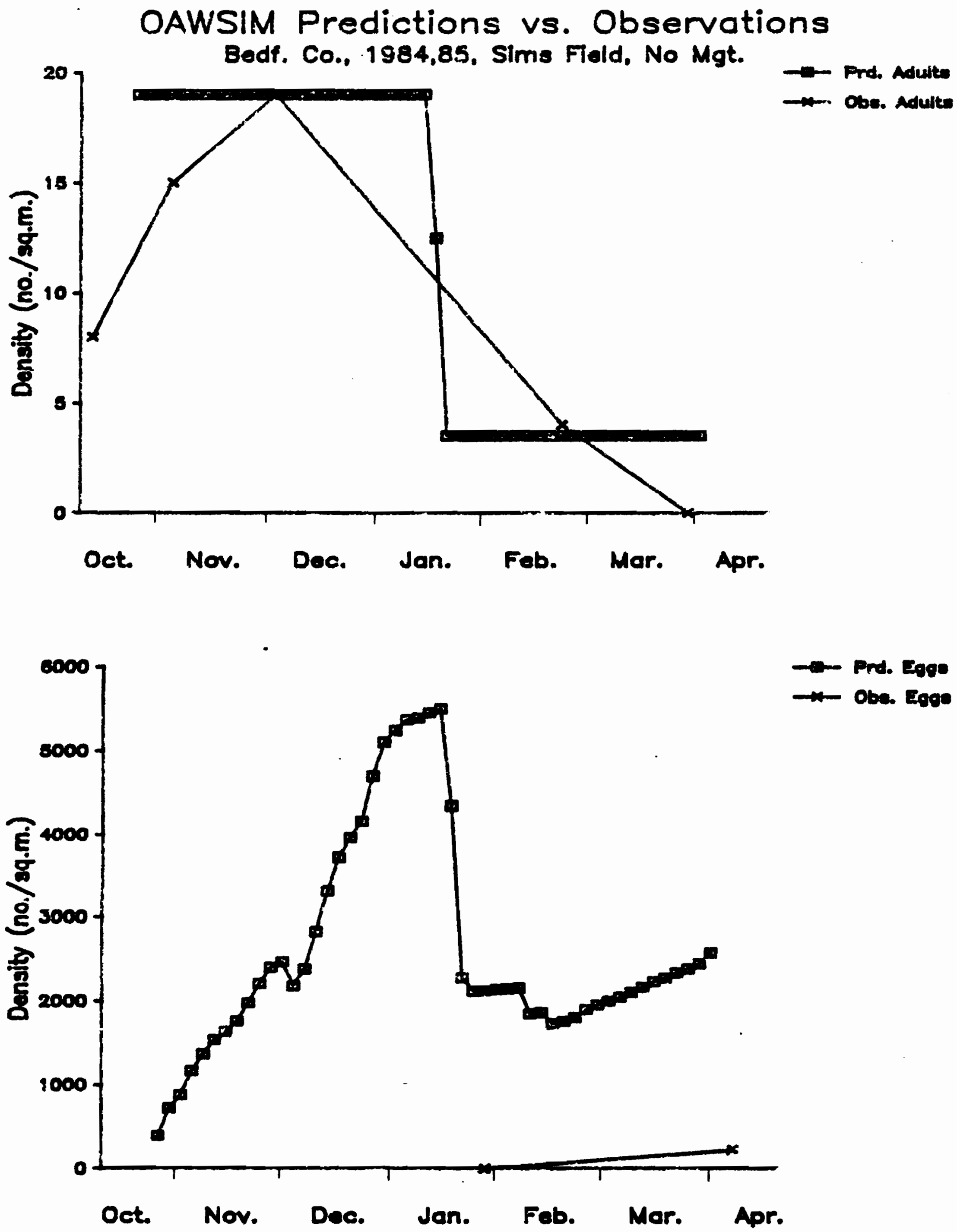


Fig. 9. Comparison of OAWSIM predictions and field measurements of alfalfa weevil adult and egg densities in Bedford Co., 1984-85, Sims field. The field received no fall regrowth management.

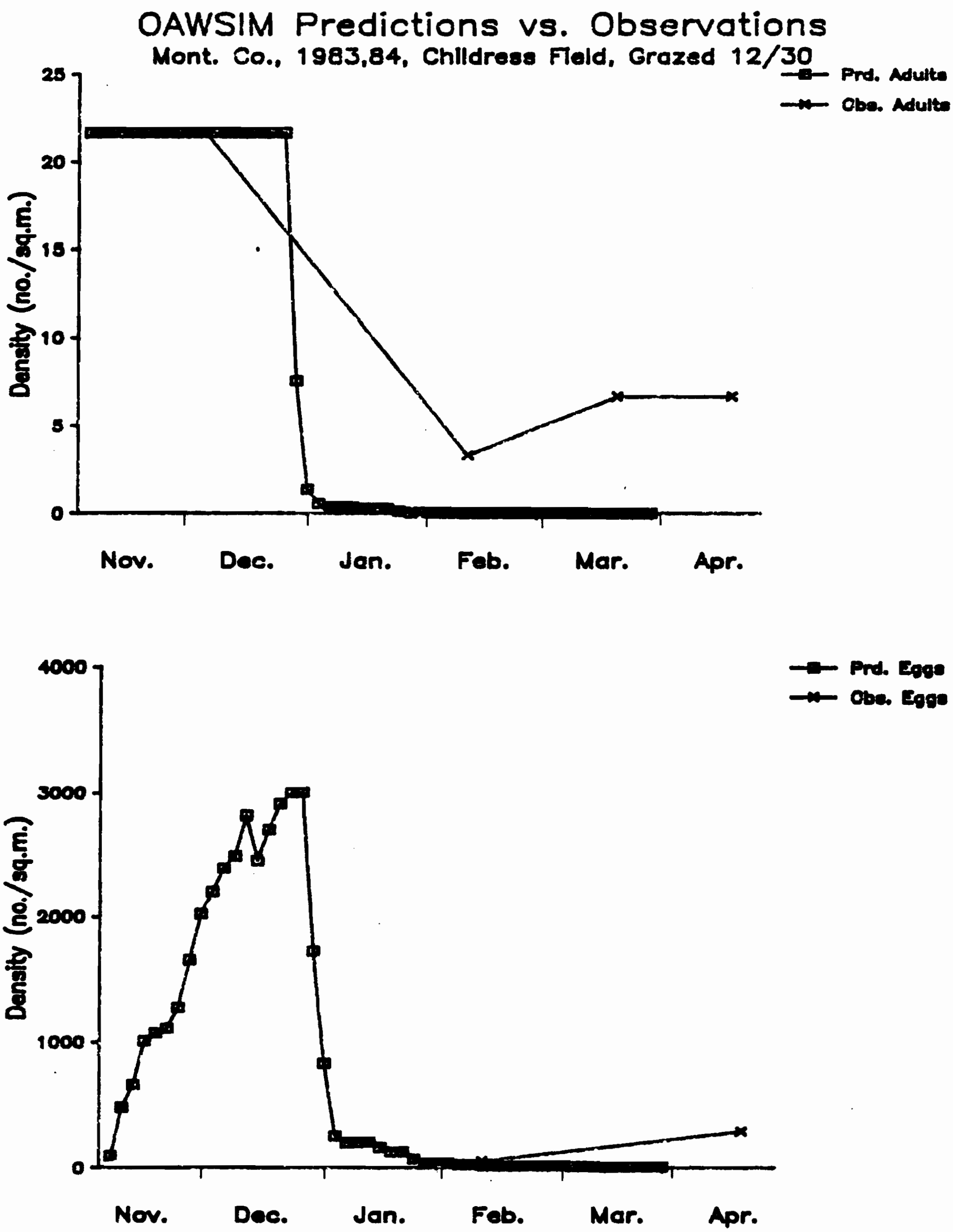


Fig. 10. Comparison of OAWSIM predictions and field measurements of alfalfa weevil adult and egg densities in Montgomery Co., 1983-84, Childress field. The field was grazed on Dec. 30.

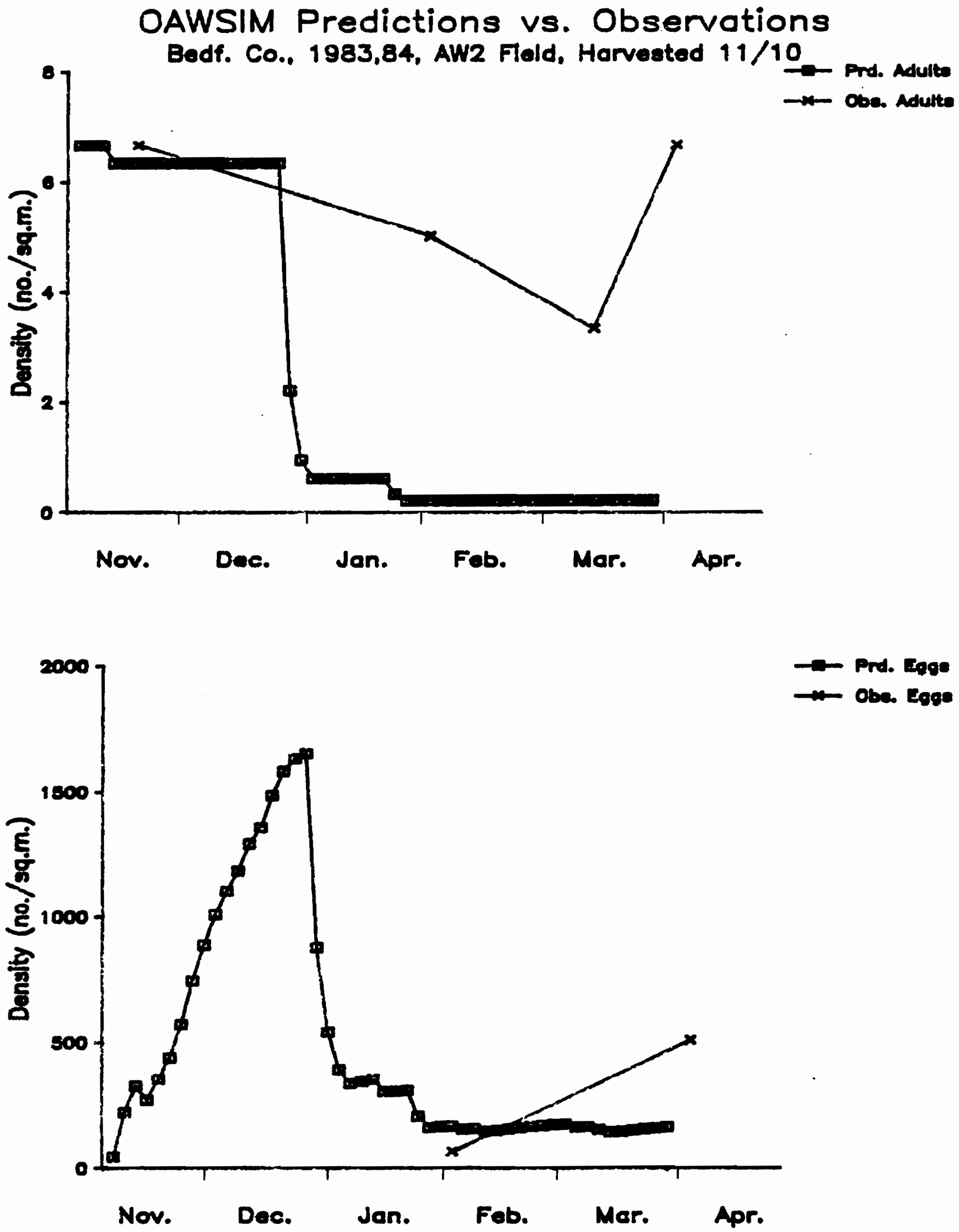


Fig. 11. Comparison of OAWSIM predictions and field measurements of alfalfa weevil adult and egg densities in Bedford Co., 1983-84, AW3 field. The field was harvested on Nov. 10.

agement techniques in hypothetical fields with identical initial conditions is presented in Figure 12. Even assuming no direct mortality attributable to regrowth management, fewer adults and eggs survive the winter in managed fields. Mortality increases due to exposure to lower temperatures following the removal of insulating plant material. Interestingly these beneficial effects are partially compensated for by higher temperatures during the day which promote higher rates of oviposition.

Tests to compare the effects of weather data from Bedford and Montgomery counties on hypothetical fields with identical initial conditions, indicated that cooler fall temperatures result in much less fall oviposition at the higher elevation. In addition colder winter temperatures cause higher mortality to both eggs and adults. Model predictions indicate temperature is the single most important factor determining adult and egg densities (Fig. 13).

DISCUSSION

OAWSIM simulates the population dynamics of overwintering alfalfa life stages. It predicts when ovipostion will occur and how many eggs will be laid. Adult and egg mortality, caused by parasites and cold temperatures, also is simulated. Validation of the model indicates refinements are needed before its predictive capability will be sufficiently accurate

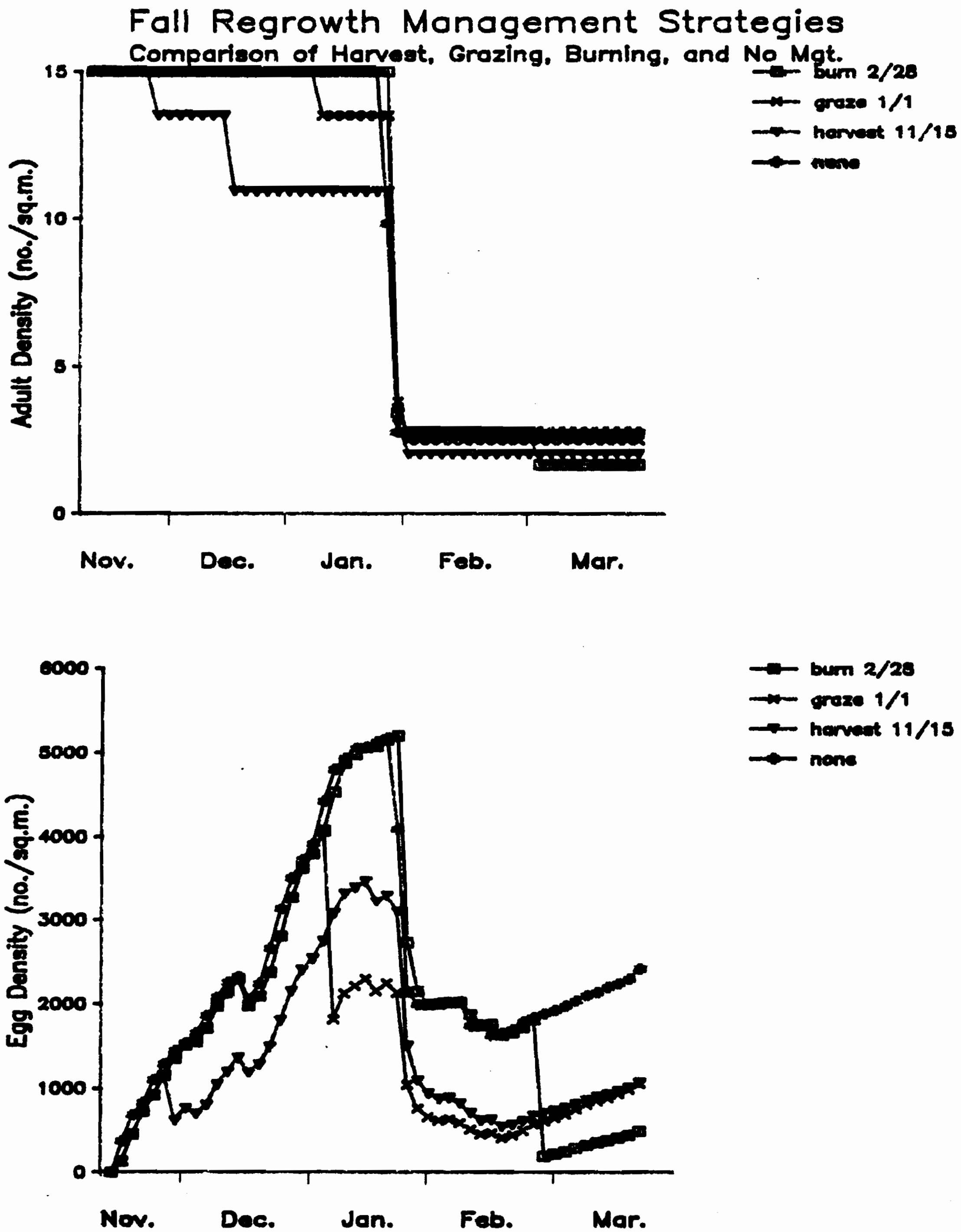


Fig. 12. Influence of fall regrowth management on OAWSIM predictions of alfalfa weevil adult and egg populations.

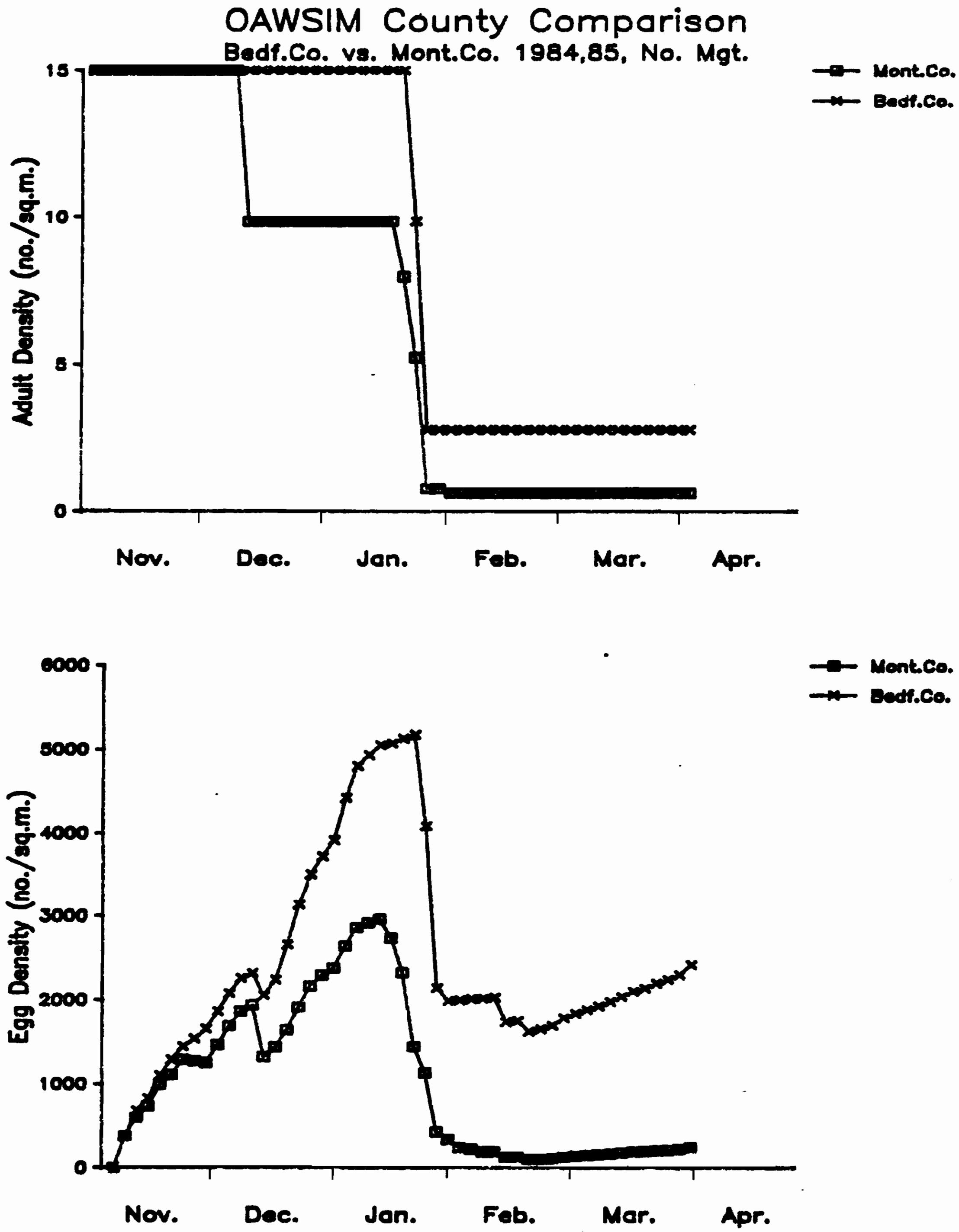


Fig. 13. Influence of winter temperature differences between Bedford and Montgomery counties on OAWSIM predictions of weevil populations.

to be useful for research or pest management purposes. At this point predicted trends in adult or egg populations generally agree with field measurements, but there are considerable discrepancies between the numbers predicted and those actually observed. This indicates the regulatory factors chosen for inclusion in the model, temperature, fall regrowth management, and parasites, are probably the major influences on winter population dynamics but the equations used to describe the relationships need refinement.

The functions relating mortality to temperature are especially crude. In the case of both eggs and adults they are based on laboratory experiments in which groups of individuals were held at constant cold temperatures for periods up to 100 days. Mortality was recorded at predetermined intervals during this period. These conditions bear little resemblance to those in the natural habitat where temperature fluctuates daily and warm temperatures are often juxtaposed with relatively cold temperatures. Experiments which more nearly simulate natural conditions are needed before the temperature-mortality relationship can be accurately simulated.

Another enhancement to the model which would improve its accuracy would be to simulate adult migration instead of assuming all weevils return together on November 1. Christensen et al. (1974) demonstrated that migration of Egyptian strain weevils, which aestivate under eucalyptus tree bark, is triggered by large differences between daily maximum and minimum temperatures. Research is needed to fill a nearly complete lack of information on migration of the eastern strain.

Finally experiments are needed which would quantify both the direct impact of fall regrowth management on overwintering weevil populations and the impact of regrowth removal on temperature in the weevil's microhabitat. Recording air temperatures at the fields rather than remote weather stations also would improve the accuracy of the model.

In spite of these shortcomings, the model has provided considerable insight into population dynamics of overwintering stages of the alfalfa weevil. It has confirmed that winter temperatures and fall regrowth management are major regulating influences, while parasites are of minor importance. OAWSIM also predicts fall ovipositon is more extensive than has been recognized. Most of these eggs are apparently killed by normal winter temperatures, but this needs to be confirmed by field measurements.

With further enhancements OAWSIM may eventually be useful in predicting levels of viable overwintering eggs in the early spring. This information would be extremely useful to pest management advisors and alfalfa growers. A future pest management program using this model might be structured as follows: Extension employees or scouts hired by grower cooperatives would sample representative fields throughout the state in late fall. At the end of the winter, these fall population estimates would be used to initialize simulation runs of the model. By using the current year's temperature records from weather stations in alfalfa growing areas, a statewide picture of the potential for damaging early spring weevil populations could be constructed. This information could be published as a map showing areas predicted to have above average, average, or below average weevil pressure. Growers in predicted trouble spots could respond by taking appropriate actions to prevent the weevil populations from reaching economically damaging levels. At the same time growers in areas of predicted below average populations would be able to save the cost of unneeded control measures.

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APPENDIX A. CODE FOR OAWSIM

```
C OAWSIM -- A MODEL TO SIMULATE OVERWINTERING OF THE ALFALFA
C WEEVIL
C -------------------------------------------------------------

C MAIN PROGRAM
C ------------

C DECLARE ARRAYS, ETC.
      DIMENSION TMAX(10,31), TMIN(10,31)
      CHARACTER ICOYR*40

C INTRODUCTION TO OAWSIM
      WRITE(*,1)
    1 FORMAT(1X,'WELCOME TO OAWSIM, A MODEL WHICH SIMULATES'
     +,/,1X,'POPULATION DYNAMICS OF OVERWINTERING STAGES',/,
     +1X,'OF THE ALFALFA WEEVIL.  THE MODEL WILL PROMPT',/,
     +1X,'TO INPUT VALUES FOR SEVERAL VARIABLES OR YOU',/,
     +1X,'CAN HAVE THEM ENTERED FROM AN INPUT FILE',/,
     +1X,'NAMED OAWSIM.INP.  OUTPUT FROM THIS SIMULATION',/,
     +1X,'WILL BE PLACED IN OAWSIM.OUT')

      PAUSE

C ENGAGE SUBROUTINE WHICH PROMPTS USER TO ENTER INITIAL
C VALUES FOR CONTROLLED VARIABLES.
      CALL INPUT(FLLDEN,PARART,MGT,ITDATA,MKDAY,AMORT,EMORT)

C ENGAGE SUBROUTINE WHICH READS IN TEMPERATURE DATA AND
C ESTIMATES TEMPERATURES AT THE SOIL SURFACE
      CALL TEMP(TMAX,TMIN,JDAY,ITDATA,MGT,MKDAY)

C ENGAGE SUBROUTINE WHICH CALCULATES INSTANTANEOUS
C TEMPERATURES AND CALLS OTHER SUBROUTINES
      CALL CALC(TMAX,TMIN,JDAY,FLLDEN,AWDEN,MGT,ITDATA,
     +TEMPI,PARART,DT,EGGS,AMORT,EMORT,MKDAY)

C PRINT FINAL MESSAGE ON THE SCREEN AT THE END OF A RUN
      WRITE(*,2)
    2 FORMAT(1X,'OUTPUT FROM THIS SIMULATION IS NOW',/,
     +1X,'AVAILABLE IN OAWSIM.OUT')

      STOP
      END
C-------------------------------------------------------------

C THIS SUBROUTINE PROMPTS THE USER TO ENTER INITIAL VALUES
C FOR CONTROLLED VARIABLES.
```

```
      SUBROUTINE INPUT(FLLDEN,PARART,MGT,ITDATA,MKDAY,AMORT,
     +EMORT)
C     ----------------
      CHARACTER ICOYR*40

C ASK USER HOW THEY WILL BE INPUTING CONTROLLED VARIABLES.

      WRITE(*,5)
    5 FORMAT(1X,'HOW WOULD YOU LIKE TO INPUT CONTROLLED',/,
     +1X,'VARIABLES?',/,/,6X,'1=FROM THE SCREEN',/,
     +6X,'2=FROM AN EXISTING FILE')

      READ(*,*)INHOW
      IF(INHOW.EQ.2)THEN
      OPEN(3,FILE='OAWSIM.INP')
      READ(3,*)FLLDEN,PARART,MGT,MMON,MDAY,AMORT,EMORT,
     +ITDATA
      GO TO 2
      ELSE

C INPUT NUMBER OF WEEVILS PER SQUARE METER.

      WRITE(*,10)
   10 FORMAT(1X,'ENTER THE INITIAL DENSITY OF ADULT WEEVILS'
     +,/,1X,'PER SQUARE METER (SUGGESTED RANGE 3-30 )')

      READ(*,*)FLLDEN

C INPUT PARASITIZATION RATE

      WRITE(*,20)
   20 FORMAT(1X,'ENTER THE PERCENT OF ADULT WEEVIL WHICH',/,
     +1X,'HAVE BEEN PARASITIZED (SUGGESTED RANGE 0-25)')

      READ(*,*)PARART

C INPUT REGROWTH MANAGEMENT PRACTICE USED.

      WRITE(*,30)
   30 FORMAT(1X,'ENTER THE NUMBER CORRESPONDING TO FALL',
     +1X,/,'REGROWTH MANAGEMENT PRACTICES USED',/,1X,
     +'1=NONE,2=HARVEST,3=GRAZE,4=BURN')

      READ(*,35)MGT
   35 FORMAT(I1)

C INPUT DATE OF REGROWTH MANAGEMNT

      IF(MGT.EQ.1)GO TO 3
      WRITE(*,31)
   31 FORMAT(1X,'ENTER THE DATE (MONTH,DAY) ON WHICH FALL',
```

```
     +1X,'REGROWTH WAS REMOVED',/,/,1X,'SUGGESTED TIMING:',
     +/,/,6X,'HARVEST: NOV 1-DEC 15 (11,1 - 12,15)',/,
     +6X,'GRAZE: DEC 15-JAN 31 (12,15 - 1,31)',/,
     +6X,'BURN: FEB 15-MAR 15 (2,15 - 3,15)',/,/,
     +1X,'THE DATE YOU CHOOSE MUST BE BETWEEN NOV 1 AND MAR
     +30')

      READ(*,*)MMON,MDAY

C INPUT DIRECT MORTALITY TO ADULTS FROM REGROWTH MANAGEMENT

      WRITE(*,32)
   32 FORMAT(1X,'CHOOSE THE AMOUNT OF DIRECT MORTALITY TO',
     +/,1X,'ADULTS ATTRIBUTABLE TO REGROWTH MANAGEMENT',/,/,
     +1X,'SUGGESTED VALUES:',/,/,
     +6X,'HARVEST: 0-30 (%)',/,
     +6X,'GRAZE: 0-30 (%)',/,
     +6X,'BURN: 50-100 (%)',/,/,
     +1X,'THE VALUE YOU CHOOSE MUST BE BETWEEN 0-100')

      READ(*,*)AMORT

C INPUT DIRECT MORTALITY TO EGGS FROM REGROWTH MANAGEMENT

      WRITE(*,33)
   33 FORMAT(1X,'CHOOSE THE AMOUNT OF DIRECT MORTALITY TO',
     +/,1X,'EGGS ATTRIBUTABLE TO REGROWTH MANAGEMENT',/,/,
     +1X,'SUGGESTED VALUES:',/,/,
     +6X,'HARVEST: 20-60 (%)',/,
     +6X,'GRAZE: 20-60 (%)',/,
     +6X,'BURN: 80-100 (%)',/,/,
     +1X,'THE VALUE YOU CHOOSE MUST BE BETWEEN 0-100')

      READ(*,*)EMORT

    3 CONTINUE

C INPUT LOCATION AND YEAR OF TEMPERATURE DATA SET

      WRITE(*,40)
   40 FORMAT(1X,'ENTER THE NUMBER CORRESPONDING TO THE',/,
     +1X,'DESIRED TEMPERATURE DATA SET:',/,/,
     +6X,'1=BEDFORD 1983-84 (WARM)',/,
     +6X,'2=BEDFORD 1984-85 (MILD)',/,
     +6X,'3=MONTGOMERY 1983-84 (COLD)',/,
     +6X,'4=MONTGOMERY 1984-85 (HARSH)')

      READ(*,45)ITDATA
   45 FORMAT(I1)
```

```
C END OF IF BLOCK WHICH DETERMINES HOW CONTROLLED VARIABLES
C ARE ENTERED
      END IF

    2 CONTINUE

C CONVERT DATE CHOSEN FOR REGROWTH MANAGEMENT TO A NUMBER
C WHICH PEPRESENTS ITS ORDINAL POSITION IN THE SIMULATION
C RUN

         IF(MMON.EQ.11)MKDAY=0+MDAY
         IF(MMON.EQ.12)MKDAY=30+MDAY
         IF(MMON.EQ.1)MKDAY=61+MDAY
         IF(MMON.EQ.2)MKDAY=92+MDAY
         IF((MMON.EQ.3).AND.((ITDATA.EQ.1).OR.(ITDATA.EQ.3)))
     +   MKDAY=121+MDAY
         IF((MMON.EQ.3).AND.((ITDATA.EQ.2).OR.(ITDATA.EQ.4)))
     +   MKDAY=120+MDAY

C OPEN FILE CONTAINING MAX-MIN TEMPERATURES

      IF(ITDATA.EQ.1)THEN
         OPEN(1,FILE='BD834.TEM')
      ELSE IF(ITDATA.EQ.2)THEN
         OPEN(1,FILE='BD845.TEM')
      ELSE IF(ITDATA.EQ.3)THEN
         OPEN(1,FILE='MT834.TEM')
      ELSE IF(ITDATA.EQ.4)THEN
         OPEN(1,FILE='MT845.TEM')
      END IF

      READ(1,199)ICOYR
  199 FORMAT(A40)

C WRITE CONTROLLED INPUTS AND HEADINGS INTO OUTPUT FILE

      OPEN(2,FILE='OAWSIM.OUT')
      WRITE(2,777)ICOYR
  777 FORMAT(1X,A40,/)
      WRITE(2,778)FLLDEN
  778 FORMAT(1X,'INITIAL WEEVIL DENSITY PER SQUARE METER = '
     +,F4.1)
      WRITE(2,779)PARART
  779 FORMAT(1X,'PARASITIZATION RATE = ',F4.1)
      IF(MGT.EQ.1)WRITE(2,780)
  780 FORMAT(1X,'REGROWTH MANAGEMENT = NONE')
      IF(MGT.EQ.2)WRITE(2,781)MMON,MDAY
  781 FORMAT(1X,'REGROWTH MANAGEMENT = HARVEST ON ',I2,'/',
     +I2)
      IF(MGT.EQ.3)WRITE(2,782)MMON,MDAY
  782 FORMAT(1X,'REGROWTH MANAGEMENT = GRAZING ON ',I2,'/',
```

```
     +I2)
      IF(MGT.EQ.4)WRITE(2,783)MMON,MDAY
  783 FORMAT(1X,'REGROWTH MANAGEMENT = BURNING ON ',I2,'/',
     +I2)
      IF(MGT.NE.1)WRITE(2,784)AMORT,EMORT
  784 FORMAT(1X,'DIRECT MORTALITY DUE TO REGROWTH',/,
     +1X,'MANAGEMENT: ',/,
     +1X,'ADULTS = ',F5.1,'%',3X,'EGGS = ',F5.1,'%')

      WRITE(2,785)
  785 FORMAT(1X,/,/,'JULIAN DAY',3X,'ADULTS/SQ. M',3X,
     +'EGGS/SQ. M',7X,'MAX',10X,'MIN')

      RETURN
      END
C----------------------------------------------------------

C THIS SUBROUTINE READS IN TEMPERATURE DATA AND ESTIMATES
C TEMPERATURES AT THE SOIL SURFACE

      SUBROUTINE TEMP(TMAX,TMIN,JDAY,ITDATA,MGT,MKDAY)
C     ---------------

      DIMENSION TMAX(10,31), TMIN(10,31)

C INPUT TEMPERATURE DATA INTO ARRAYS.

         MO=10
      DO 100 I=1,5
         MO=MO+1
         IF(MO.EQ.13)MO=1
         ND=31
         IF(MO.EQ.11)ND=30
         IF(MO.EQ.2)ND=28
         IF(ITDATA.EQ.1.AND.MO.EQ.2)ND=29
         IF(ITDATA.EQ.3.AND.MO.EQ.2)ND=29
         READ(1,200)MON,(TMAX(I,JJ),JJ=1,ND)
         READ(1,200)MON,(TMIN(I,KK),KK=1,ND)
  200    FORMAT(I2,1X,31F3.0)

  100 CONTINUE


C CONVERT AIR TEMPERATURES TO SOIL SURFACE TEMPERATURES
C TAKING INTO CONSIDERATION THE INSULATING AFFECT
C OF FALL REGROWTH

C A = DEGREES F ADDED TO MINIMUM TEMPERATURES AT THE SOIL
C SURFACE DUE TO THE INSULATING PROPERTIES OF FALL REGROWTH
      A=5.4
      B=1.0
```

```
C AA = DEGREES F ADDED TO MAXIMUM TEMPERATURES AT THE SOIL
C SURFACE DUE TO THE ABSENCE OF INSULATION FROM FALL
C REGROWTH
      AA=5.4
      BB=1.0

           KDAY=0
           MO=10
      DO 103 J=1,10
           MO=MO+1
           IF(MO.EQ.13)MO=1
           ND=31
           IF(MO.EQ.11)ND=30
           IF(MO.EQ.2)ND=28
           IF(ITDATA.EQ.1.AND.MO.EQ.2)ND=29
           IF(ITDATA.EQ.3.AND.MO.EQ.2)ND=29
         DO 104 K=1,ND
           KDAY=KDAY+1
           IF(MGT.EQ.1)THEN
             TMIN(J,K)=A+B*TMIN(J,K)
           ELSE IF(KDAY.LT.MKDAY)THEN
             TMIN(J,K)=A+B*TMIN(J,K)
           ELSE
             TMAX(J,K)=AA+BB*TMAX(J,K)
           END IF
  104    CONTINUE
  103 CONTINUE

      RETURN
      END
C-------------------------------------------------------------

C THIS SUBROUTINE CALCULATES INSTANTANEOUS TEMPERATURES AND
C CALLS OTHER SUBROUTINES

      SUBROUTINE CALC(TMAX,TMIN,JDAY,FLLDEN,AWDEN,MGT,
     +ITDATA,TEMPI,PARART,DT,EGGS,AMORT,EMORT,MKDAY)
C     ---------------

      DIMENSION TMAX(10,31), TMIN(10,31)

C INITIALIZE CONSTANTS
      DT=.1
      Q1=DT*10.
      PERIOD=3.14159/5.
      N=1/DT

C MONTHLY LOOP

          JDAY=304
```

```
          KDAY=0
          MO=10

      DO 105 IMO=1,5
          MO=MO+1
          IF(MO.EQ.13)MO=1

C $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C PRINT MONTHLY POPULATION VALUES TO THE SCREEN WHILE THE
C PROGRAM IS RUNNING
      WRITE(*,55)JDAY,AWDEN,EGGS
   55 FORMAT(1X,I3,8X,F5.2,8X,F7.2)
C $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

C DAILY LOOP

         ND=31
         IF(MO.EQ.11)ND=30
         IF(MO.EQ.2)ND=28
         IF(ITDATA.EQ.1.AND.MO.EQ.2)ND=29
         IF(ITDATA.EQ.3.AND.MO.EQ.2)ND=29

             DO 106 IDAY=1,ND
                HRANG=(TMAX(IMO,IDAY)-TMIN(IMO,IDAY))/2.
                TMEAN=(TMAX(IMO,IDAY)+TMIN(IMO,IDAY))/2.

                HTIME=0.0
                JDAY=JDAY+1
                IF(JDAY.EQ.366)JDAY=1
                KDAY=KDAY+1

C REDUCE ADULT POPULATION BY DIRECT EFFECTS OF REGROWTH
C MANAGEMENT

      IF(JDAY.EQ.305)AWDEN=FLLDEN
      IF((MGT.NE.1).AND.(KDAY.EQ.MKDAY))
     +AWDEN=AWDEN*(0.01*(100.0-AMORT))

C REDUCE EGG POPULATION BY DIRECT EFFECTS OF REGROWTH
C MANAGEMENT

      IF(JDAY.EQ.305)EGGS=0.0
      IF((MGT.NE.1).AND.(KDAY.EQ.MKDAY))
     +EGGS=EGGS*(0.01*(100.0-EMORT))

C CALL SUBROUTINE WHICH WRITES RESULTS TO OUTPUT FILE

      CALL PRINT(JDAY,AWDEN,EGGS,TMAX,TMIN,IMO,IDAY)

C WITHIN DAY LOOP (DT)
               DO 107 IDT=1,N
```

```
C CALCULATE INSTANTANEOUS TEMPERATURES FROM MAX-MIN
                  HTIME=HTIME+Q1
                  THETA=HTIME*PERIOD
                  TEMPI=TMEAN+HRANG*SIN(THETA)

C ENGAGE SUBROUTINE WHICH ESTIMATES ADULT MORTALITY
                  CALL AWMORT(AWDEN,TEMPI,DT)

C ENGAGE SUBROUTINE WHICH ESTIMATES OVIPOSITION RATE
                  CALL OVIPOS(AWDEN,EGGS,PARART,TEMPI,DT)

C ENGAGE SUBROUTINE WHICH ESTIMATES EGG MORTALITY
                  CALL EGGMORT(EGGS,TEMPI,DT)

C END OF WITHIN DAY LOOP
 107              CONTINUE
C END OF DAILY LOOP
 106          CONTINUE
C END OF MONTHLY LOOP
 105      CONTINUE

C $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C WRITE ON THE SCREEN THE POPULATION OF EGGS AND ADULTS
C ON LAST DAY OF SIMULATION RUN
      WRITE(*,56)JDAY,AWDEN,EGGS
   56 FORMAT(1X,I3,8X,F5.2,8X,F7.2)
C $$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$

      RETURN
      END
C --------------------------------------------------------------

C THIS SUBROUTINE ESTIMATES MORTALITY TO ADULT WEEVILS

      SUBROUTINE AWMORT(AWDEN,TEMPI,DT)
C     -----------------

C REDUCE WEEVIL POPULATION BECAUSE OF LOW TEMPERATURES
      IF(TEMPI.LE.14.0)
     +AWDEN=AWDEN*(.01*(100.-(9.909524+(0.988383*DT))))

      RETURN
      END
C --------------------------------------------------------------

C THIS SUBROUTINE ESTIMATES THE OVIPOSITION RATE

      SUBROUTINE OVIPOS(AWDEN,EGGS,PARART,TEMPI,DT)
C     -----------------
```

```
C CORRECT WEEVIL POPULATION FOR PARASITIZED INDIVIDUALS
      CAWDEN=AWDEN*(0.01*(100.-PARART))

C CORRECT FOR SEX RATIO
      FAWDEN=CAWDEN/2.0

C CALCULATE NUMBER OF EGGS LAID AND ADD TO TOTAL EGGS

      ADDEGG=0.0
      IF(TEMPI.GT.33.0)
     +ADDEGG=FAWDEN*(DT*(-23.03+(0.7017*TEMPI)))
      EGGS=EGGS+ADDEGG

      RETURN
      END
C -------------------------------------------------------

C THIS SUBROUTINE ESTIMATES EGG MORTALITY

      SUBROUTINE EGGMORT(EGGS,TEMPI,DT)
C     ------------------

C REDUCE EGGS BECAUSE OF LOW TEMPERATURES
      IF(TEMPI.LT.21.2)
     +EGGS=EGGS*(0.01*(100.0-(3.772749+(1.831483*DT))))

      RETURN
      END
C ------------------------------------------------------

C THIS SUBROUTINE PRINTS THE RESULTS

      SUBROUTINE PRINT(JDAY,AWDEN,EGGS,TMAX,TMIN,IMO,IDAY)
C     ----------------
      DIMENSION TMAX(10,31), TMIN(10,31)

C WRITE JULIAN DAY,ADULT DENSITY, AND EGG DENSITY TO OUTPUT
C FILE

      WRITE(2,666)JDAY,AWDEN,EGGS,TMAX(IMO,IDAY),TMIN(IMO,
     +IDAY)
  666 FORMAT(5X,I3,8X,F5.2,8X,F7.2,8X,F5.1,8X,F5.1)

      RETURN
      END
```

Bedford, Virginia Temperatures Nov. 83 - Mar. 84, Nov. 84 - Mar. 85

Nov	MAX	62	66	73	67	50	54	60	65	69	64	59	50	45	54	48	52	47	62	70	65	66	76	67	61	58	62	62	53	54	55		59.9
	MIN	39	40	51	47	38	40	34	34	38	55	42	34	29	29	38	40	42	41	45	49	44	47	44	52	35	39	32	49	41	33		40.7
Dec	MAX	53	45	46	56	62	55	51	46	48	58	55	54	58	53	54	49	48	45	41	36	28	44	42	39	16	22	22	37	35	37	29	44.0
	OBS																									34							
	MIN	40	28	43	37	38	44	33	27	25	34	41	44	49	37	43	37	37	25	23	23	23	28	35	-6	-1	6	6	23	28	11	12	28.2
	OBS																														29		
Jan	MAX	45	42	46	54	53	54	48	54	57	46	39	35	33	43	37	35	46	41	34	28	27	33	47	42	51	59	60	53	43	41	38	44.0
	MIN	15	20	31	31	36	40	36	29	36	32	31	16	24	29	26	29	29	31	29	12	8	5	14	33	36	28	29	32	28	25	25	26.6
Feb	MAX	42	54	52	55	48	38	33	45	64	62	59	69	67	63	67	64	65	66	69	65	56	60	57	68	64	51	48	42	38			56.2
	MIN	22	20	32	30	27	29	22	16	36	28	39	38	46	52	44	37	46	42	40	44	34	26	39	37	42	30	32	30	24			33.9
Mar	MAX	43	47	50	45	45	54	50	50	46	42	48	48	42	62	67	74	66	66	65	67	60	52	55	64	62	57	59	58	45	54	52	54.7
	OBS																																
	MIN	20	27	25	22	37	39	30	28	17	20	28	24	30	37	30	38	36	41	44	45	39	36	40	28	37	43	40	44	38	38	35	33.5
	OBS																																

Nov	MAX	61	64	57	48	60	60	48	50	55	63	60	48	48	53	62	57	48	46	48	39	36	41	57	57	56	61	59	56	48	55		53.4
	MIN	50	58	33	43	45	42	28	25	30	32	45	36	31	32	26	26	32	31	38	29	17	16	16	24	25	26	31	47	32	24		32.3
Dec	MAX	54	51	55	49	37	35	30	47	53	46	53	53	71	67	74	66	72	72	65	60	54	61	55	47	47	47	62	74	77	70	60	56.9
	MIN	24	24	39	26	28	28	12	25	24	28	40	32	40	41	47	49	49	53	50	53	43	43	32	23	41	21	31	46	50	56	42	36.8
Jan	MAX	68	62	54	36	39	48	46	42	35	32	39	33	42	47	44	35	41	40	38	32	10	27	36	44	43	41	39	38	37	40	42	40.3
	MIN	44	49	35	33	32	29	27	35	24	23	27	20	22	29	22	17	27	30	17	0	-10	7	16	25	31	15	18	30	29	17	31	24.2
Feb	MAX	40	37	34	32	30	49	40	33	48	50	48	44	34	44	42	40	48	50	52	53	59	70	73	79	75	65	57	53				49.3
	MIN	35	33	20	22	23	27	27	15	15	19	23	32	24	24	23	15	20	28	38	28	23	36	39	42	59	43	41	28				28.6
Mar	MAX	54	63	59	53	65	61	52	62	66	65	63	57	63	62	55	58	59	49	59	73	69	41	60	61	56	65	76	83	85	83	70	62.8
	MIN	26	39	29	29	37	28	25	35	47	39	35	44	41	51	37	27	38	28	28	34	41	31	36	43	36	30	36	53	58	65	47	37.8

Blacksburg, Virginia Temperatures Nov. 83 - Mar. 84, Nov. 84 - Mar. 85

Nov	MAX	61	66	67	67	48	40	58	60	65	62	60	45	38	40	52	41	42	40	59	68	62	59	68	64	59	43	60	55	65	43		55.2
	MIN	25	25	28	30	22	32	25	28	20	36	30	19	15	14	27	29	34	24	22	32	34	27	30	34	21	25	18	24	27	19		25.9
Dec	MAX	48	42	43	47	60	64	57	35	46	47	59	45	51	50	50	50	41	43	45	35	26	32	43	35	13	9	23	35	35	28	21	40.6
	MIN	19	18	19	26	26	37	19	18	13	15	25	30	36	25	30	29	28	17	20	22	19	19	21	10	-8	-7	-3	20	25	-2	4	18.4
Jan	MAX	37	47	38	42	49	45	46	38	50	57	43	35	30	33	37	34	35	43	31	23	22	20	40	45	50	45	55	52	45	40	36	40.1
	MIN	6	16	25	22	22	32	29	23	25	32	18	13	15	20	24	26	25	28	19	5	3	-3	13	16	33	26	27	26	28	24	20	20.6
Feb	MAX	27	40	55	51	52	36	28	20	37	62	55	55	66	58	60	51	61	64	65	68	44	51	61	42	61	43	51	32	39			49.5
	MIN	14	13	21	29	27	25	10	14	17	24	35	34	36	44	31	32	41	42	43	38	28	26	28	32	35	27	28	25	19			28.2
Mar	MAX	28	36	36	46	48	53	44	43	46	32	40	42	45	45	58	72	67	63	65	71	57	44	45	65	57	54	52	60	45	40	43	49.7
	MIN	16	20	30	22	25	34	26	24	12	13	19	24	28	30	27	30	31	30	40	46	35	34	38	25	30	43	38	43	37	33	30	29.4

Nov	MAX	69	65	61	48	52	54	47	56	55	63	65	49	37	47	58	64	53	47	42	44	40	41	45	54	59	60	68	62	59	47		53.7
	OBS							61																									
	MIN	51	49	30	31	38	43	25	21	23	32	38	30	27	28	29	32	28	26	35	29	13	15	16	19	22	23	28	45	30	20		29.2
Dec	MAX	59	60	54	50	45	36	42	28	48	54	48	60	62	70	69	75	64	70	68	67	55	58	57	49	51	48	52	66	73	68	58	56.9
	MIN	22	20	26	24	26	26	7	7	24	25	30	29	28	34	36	39	41	47	48	47	43	42	26	21	22	16	32	34	41	50	39	30.7
Jan	MAX	57	63	52	37	35	33	52	43	35	34	33	30	28	30	43	25	39	37	32	28	20	11	29	32	40	40	26	40	33	35	39	35.8
	MIN	43	47	34	30	25	17	19	28	15	20	22	14	15	19	13	8	10	20	24	-2	-18	-2	10	12	22	11	8	12	20	15	19	17.1
Feb	MAX	35	42	39	32	30	38	41	34	23	34	52	46	36	25	37	32	35	40	51	45	51	57	67	68	71	62	64	53				44.3
	MIN	20	20	14	15	21	22	20	11	12	16	22	29	19	19	13	9	17	22	26	25	24	29	41	46	48	43	44	24				24.0
Mar	MAX	55	54	58	57	63	62	48	56	59	60	63	52	55	65	62	52	58	50	41	62	68	49	46	53	59	51	67	72	77	75	85	59.2
	MIN	27	33	27	28	40	25	24	25	41	35	32	35	35	37	33	23	27	22	21	29	40	29	29	36	37	27	34	41	60	59	45	33.4

VITA

Daniel Joseph Hilburn was born on 6 November 1956 in Cloverdale, California. He attended primary schools in Lakeport, Ca., New Glouster, Me., Poland, Me., Glasgow, Mt., Cape Elizabeth, Me., and Hollis, Me. After graduation from Salmon Falls School in June 1974, he enrolled in Middlebury College in Middlebury, Vermont, graduating with a B.A. degree in Biology in 1978. He taught biology at Camden-Rockport High School in Camden, Maine in 1978-79 before enrolling as a graduate student at the University of Maine at Orono. His M.S. degree in Entomology was completed in 1981 with a thesis entitled: The Effects of Aerial Spraying for Spruce Budworm with Carbaryl and *Bacillus thuringiensis* on Non-Target Terrestrial Arthropods. In the same year he accepted a position as a Lab Specialist in the Insect Identification Lab at Virginia Polytechnic Institute and State University. There he pursued his PhD as a part-time graduate student in the Department of Entomology. On August 22, 1981 he married Lucy Elizabeth Caswell. Their daughter, Alison Emily, was born on July 29, 1985.

Daniel J. Hilburn