Effect of Cover Crop on Apple Leafroller Populations, Leafroller Parasitism and Selected Arthropods in an Orchard Managed Without Insecticides.

by

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ABSTRACT

In Washington State the Pandemis leafroller, *Pandemis pyrusana* (Kereta) and obliquebanded leafroller, *Choristoneura rosaceana* (Harris) are serious pests in orchards in which mating disruption is used to control codling moth, *Cydia pomonella*. Resistance to organophosphate insecticides exacerbates the problem. Additionally, many question the dependence on insecticides and call for ecologically-based pest management. Parasitoid and predator conservation and augmentation via insecticide reduction and habitat manipulation are tactics proposed to achieve biological control.

The objectives of these studies were to: 1) evaluate and compare development of leafroller populations and their biological control by parasitoids in an apple orchard with either a grass or alfalfa cover and in which no insecticides were used; 2) evaluate the influence of cover crops on the general orchard arthropod population in an orchard managed without insecticides; 3) evaluate the use of alfalfa as an orchard cover crop on fruit tree growth and development; and 4) conduct initial testing of strategies for augmenting the leafroller parasitoid *Colpoclypeous florus*. Experiments were conducted in an East Wenatchee, Washington apple orchard, over four years. Plots were
approximately 0.5 ha in size and were sown to either grass cover or alfalfa. Insecticide applications were eliminated.

In the absence of broad-spectrum insecticides leafroller populations initially rose to high levels and then dramatically declined. A granulovirus may have been primarily responsible for the decline. Leafroller parasitoids also contributed to leafroller biological control though not extensively. There were no differences in leafroller populations between ground cover treatments. In some instances parasitism was slightly greater in the alfalfa cover plots but this did not seem of any practical significance. Six species were identified in the parasitoid complex. No secondary arthropod pest achieved pest status in either ground cover during the study. Codling moth however became a serious problem in year four. Attempts to augment *C. florus* populations by seeding parasitized *Ancylis comptana fragaria* failed. Attempts to establish *Xenotemna pallorana* on the alfalfa cover to serve as an alternate host for *C. florus* were likewise unsuccessful. Alfalfa as a cover crop imposed no adverse effects on tree growth and development during the duration of these studies.
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For my sixteen year old daughter Noelle and twelve year old son Nathan, with hope that this, in some small way, will contribute to the creation of a more sustainable and meaningful future for them, others around the world and generations yet to be.
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CHAPTER ONE

INTRODUCTION, OBJECTIVES AND REVIEW OF LITERATURE

Introduction and Objectives

Input intensive, chemically based agriculture, often referred to as industrial or conventional agriculture, developed and became widely adopted over the last century and, in that system, synthetic pesticides quickly became the standard and foremost strategy for insect control. The modern era of insect pest management emphasizing insecticides is only about 70 years old (National Research Council, 1996).

Annual U.S. use of all pesticides was 260 million kilograms in 1992. Worldwide pesticide use was estimated at 2,227 million kilograms in 2000 (McGinn, 2000; National Research Council, 1996). Pesticide use is decreasing in some instances but the Environmental Protection Agency (EPA) reports overall insecticide use on all agricultural lands in the U.S. has increased in recent years from 95.5 million kilograms in 1986 to 114.6 million kilograms in 1995; a 20% increase (Benbrook, 1996). Between 1991 and 1995 overall pesticide use in California rose 31% and the use of carcinogenic pesticides more than doubled (Steingraber, 1998).

High input, chemical based agriculture is a worldwide phenomenon. In the U.S., however, it is the actualization of a particular vision of agriculture and its role in national and international economic development with accompanying strategies, science and policies directed toward its achievement. Chemical based agriculture is pervasive, ubiquitous and deeply ingrained in the consciousness of the agriculture sector as well as that of the populace. So much so that it seems difficult, if not impossible, for most to imagine an alternative (Fretz et al., 1993; Danbom, 1997; Ikerd 2002; Stauber et al., 1995; van den Bosch, 1978). Regarding pesticide use in agriculture
Pedigo (2002) stated, “...pesticides are some of the most important chemicals used for the well being of human populations. They are indispensable...” and “the quantity and quality of our food and fiber production could not be maintained without substantial pesticide inputs”.

Pimental et al. (1992) shared similar sentiment saying pesticides, despite their high environmental and social cost, are and will continue to be valuable pest management tools. Certainly this paradigm has shaped our modern agriculture systems as well as the thinking and development within the university, the boardroom, the government and on the farm (Benbrook, 1996; van den Bosch, 1978).

In general, modern, industrialized agriculture systems are characterized as 1) highly specialized monocultures emphasizing maximum yields, 2) utilizing improved varieties which are dependent upon fertilizers, pesticides and irrigation, 3) increasingly seeking and achieving standardization, 4) being highly mechanized, 5) being biologically and ecologically simplified and 6) utilizing many purchased, off-farm inputs. (Danbom, 1997; Fretz et al., 1993; Ikerd, 2002; Lewis et al., 1997; Luna and House, 1990; National Research Council, 1996; Norris, R. F. 1986). Ikerd (2002) characterized our current efforts to complete agriculture industrialization as the last gasp of the industrial era. He discusses the industrialization of agriculture (high input mechanization, fertilizers and pest control materials) and contends it probably lagged behind the rest of industrialization because its biological systems were the least suited and the most difficult to industrialize. “Agriculture by nature”, Ikerd says, “doesn’t fit industrialization and has to be forced to conform”. Most notably industrial agriculture relies on extensive use of agrichemicals in the form of herbicides, fungicides and insecticides for pest control. The reliance on pesticides as the foremost pest management strategy, many would contend, is a prime manifestation of the severe shortcomings of the industrialized agriculture model.
Regardless, the industrial, high input agriculture model has been highly successful in terms of productivity (Fretz et al., 1993; Thrupp, 1996; Pédigo, 2002) with yields tripling since the 1940’s (McGinn, 2000; Thrupp, 1996; York, 1991). In many major world production regions yields are plateauing or even declining and many believe that the benefits of high input, industrial agriculture have been fully realized (York, 1991). Concomitantly we have come to recognize that the adoption of the industrial agriculture model and methodologies, with its phenomenal productivity, has exacted an accompanying price (Danbom, 1997; Fretz et al., 1993; Ikerd, 2002; Kimbrell, 2002; Lewis et al., 1997; Pimental et al., 1992).

According to Ikerd (2002) the most obvious consequence has been the specialization, standardization and consolidation of farming operations resulting in increasingly fewer farms, farm families and more recently the ‘corporatization’ of agriculture. Others cite additional, undesirable socio-economic results of industrialized agriculture (Pimental et al., 1992; Stauber et al., 1995; Tette and Jacobson, 1992; van den Bosch, 1978). Environmental/ecological consequences and concerns abound (Altieri and Letourneau, 1982; Benbrook, 1996; Colburn et al., 1997; Farming and the Environment, 2000; Hill et al., 1999; Kimbrell, 2002; Lee, 1992; Lewis et al., 1997; Pimental et al., 1992; Shiva, 1993; Soule and Piper, 1992; Stauber et al., 1995; Tilman, 1999). Fretz (1993) summarized the “rapidly emerging interest” and “concerns” expressed by farmers, scientists, politicians and our citizenry to include:

"Increased cost and uncertain availability of energy and farm chemicals;

Increased resistance of pests to chemical controls;

Declining soil productivity due to erosion, accompanied by loss of organic matter and plant nutrients;"
Pollution of surface waters with agricultural chemicals and sediment;

Depletion of finite reserves of concentrated plant nutrients (e.g., rock phosphate);

Hazards to human and animal health from pesticides and feed additives;

Destruction of wildlife, bees, and other beneficial insects by pesticides;

Detrimental effects of agricultural chemicals on food quality;

Decrease in the number of farms, particularly family farms."

Many citizens and consumers now believe that residues of synthetic agrichemicals in or on foods represent a significant health risk. Adverse environmental impacts of synthetic agrichemicals have also caused consumers to oppose the use of these materials in crop production (Wiles et al., 1999; Merwin and Pritts, 1993; National Research Council, 1996; Reganold et al., 2001). As Lewis et al. (1997) and Hill et al. 1999) convey there is now an abundance of literature documenting the negative (long and short term) side effects of our narrowly conceived pest interventions regarding agricultural use of pesticides. Others convey a similar assessment about long-term dependence upon chemically based pest management strategies (Benbrook, 1996; Colburn et al., 1997; Hewitt and Smith, 1995; Lewis et al., 1997; Luna and House, 1990; Pimental et al., 1992; National Research Council, 1996; Thrupp, 1996; van den Bosch, 1978; Wiles et al., 1999). As such there is a resounding call to broaden and restructure agricultural system pest management strategies with the objective of significantly reducing or nearly eliminating the use of pesticides (National Research Council, 1996; Lewis 1997; Stary and Pike, 1999; van den Bosch, 1978).

Many call for the development and implementation of ecologically sound agriculture systems that rely first and foremost on biologically based pest management mechanisms with very
selective, environmentally benign pesticides being used as a tool of last resort (Bugg and Pickett, 1998; National Research Council, 1996; Stanleley, 1996). To this end there have been numerous studies of arthropod fauna and pest control strategies in various “alternative” agricultural systems. Amid varying outcomes these studies clearly indicate the need and importance of “evaluating baseline arthropod and other biotic activity in systems that are not disrupted by agrichemical inputs” (Bugg and Pickett, 1998) as the starting point.

Generally pesticide use is relatively great on high value fruit and vegetable crops; up to 15 pounds of active ingredient and at a cost of several hundred dollars per acre. (Benbrook, 1996; National Research Council, 1996). Apples are one of the crops that receives the highest number of pesticide sprays on a per acre basis (Goonewardene et al., 1990; Merwin, 1993). Additionally apple is a crop on which some of the most criticized and soon to be scrutinized insecticides (broad spectrum neurotoxins primarily) are routinely used. To their credit Washington apple producers have adopted several pest management advances, such as pest and predator monitoring, use of phenology models and pheromone based mating disruption, that have resulted in measurable reduction in insecticide use (Jones, 2002). The advent of pheromone based mating disruption for the management of codling moth (Cydia pomonella L.) and the subsequent reduction of broad-spectrum insecticides resulted in the emergence of leafrollers as a major insect pest of apple in Washington State and this represented a barrier to the potential to redesign the apple pest management system. In orchards using codling moth mating disruption the potential for biological control of leafrollers through the conservation and enhancement of insect parasitoids via pesticide reduction and habitat manipulation is at least possible. However this potential has not been appreciably investigated. As such the objectives of this study were to:

1. Evaluate and compare the development of leafroller populations and their biological control by parasitoids in an apple orchard with either grass or alfalfa cover crops and
in which codling moth mating disruption is used as a management option with no in-season use of insecticides.

2. Compare the influence of grass and alfalfa cover crops on general orchard arthropod populations (common pests and natural enemies) in orchards in which codling moth mating disruption and no insecticides are used during the growing season.

3. Evaluate the potential to establish an alternate, overwintering host, strawberry leafroller (*Xenotemna pallorana* Robinson) for the leafroller parasitoid *Colpoclypeous florus* Walker (Hymenoptera: Eulophidae) in alfalfa cover.

4. Evaluate alfalfa as a cover crop on apple tree vigor, fruit size and fruit quality in contrast to a standard grass cover.

5. Identify management strategies and challenges of alfalfa cover crops in an apple orchard.

**Review of the Literature**

**Problems associated with pesticide use in agriculture**

Despite the touted desirability and advantage of pesticide use in agriculture many shortcomings and unanticipated negative effects from their extensive use have become evident. These include pest resistance, induced pest problems, increased crop loss from pests, crop damage from misdirected pesticide application, environmental contamination and damage, toxicity to and endangerment of non-target species, food safety and acute and chronic human health effects.

Resistance to insecticides, an “ecological backlash” phenomenon, has emerged as a frequent and important problem associated with pesticide use. Insecticide resistance occurs when the
susceptibility of an insect population shifts in relation to a specific insecticide or even class of insecticides. Insects have proven to be some of the most adaptable animals on earth in their response to selective pressures induced by pesticides. Insect populations generally have multiple mechanisms of resistance to pesticides with each mechanism potentially responding to different materials and modes of action (Pedigo, 2002). Many insects, including major agricultural pests, have developed resistance to one or more class of insecticide (Georghiou, 1986; Gould, 1991). Croft (1982) reviewed cases of arthropod resistance in North American apple orchards to organophosphate insecticides and the application of resistance management strategies.

Farmers typically respond to initial resistance development by applying higher rates of an insecticide more often. This generally accelerates resistance development and exacerbates the problem. When the pesticide farmers have been using is no longer effective they usually switch to another class of insecticide and repeat the cycle. This phenomenon has been referred to as the ‘pesticide treadmill’ (Dennehy et al., 1987; van den Bosch, 1978). Resistance to insecticides and the pesticide treadmill has become commonplace (Pedigo, 2002). Today more than 500 insect pest species are known to be resistant to insecticides and the list continues to grow (Benbrook 1996; Lewis et al., 1997; National Research Council, 1996; Thrupp, 1996). Indeed pesticide failures seriously threaten several major food and fiber crops (Benbrook, 1996; Tabasnik and Croft, 1985). The National Research Council (1996) suggests that continued reliance on insecticides makes it “impossible to step off the treadmill” and that experience tells us resistance should be anticipated as a possible outcome of insecticide based pest control. As Lewis (1996) said “experience... substantiates the fact that therapeutic interventions into any system are effective only for short term relief because these externalities are soon “neutralized” by countermoves within the system”. According to Benbrook (1996), “…reliance on pesticides has been on the increase for twenty years. More applications are being made per acre of
farmland...and on average a greater number of active ingredients are needed to manage pests effectively. Indeed the quantity of pesticides applied in many settings is still rising”. McGinn (2000) echoes Benbrook’s sentiment saying “modern agriculture has a serious chemical dependency- an addiction to pesticides”. Certainly Washington apple farmers remain conceptually and functionally reliant upon pesticides.

Even with a 10-fold increase in the use of insecticides in the U.S.A. between 1945 and 1989 and the accompanying direct costs ($8.8 billion in the U.S., an increase of 35% between 1983 and 1993) incurred by farmers (Aspelin, 1996; Benbrook, 1996), crop losses in the U.S. from insects to have doubled from 7% to 13% during that same time. Pests still destroy 37% of all potential U.S. food and fiber crops despite increased pesticide use (Pimental et al., 1992). Van den Bosch (1978) concurred saying at the onset of the synthetic pesticide era the U.S.A. approximately 22.7 million kilograms of insecticides were used and incurred pre-harvest crop losses due to insect pests of approximately 7%. Thirty or so years later he estimated a 272.7 million kilogram insecticide use and pre-harvest crop losses of 13%. Of this he concluded, “In other words a major reward of our 11-fold increase in insecticide use has been a doubling of the bug problem”. Lewis (1996) more recently reported that on a worldwide basis, despite the intensification of chemical based pest management, overall crop losses due to disease, weed and insect pests has risen from 34.9% in 1965 to 42.1% in 1990.

Increased pre-harvest crop losses may be due in large part to resurgence or replacement (secondary) pest outbreaks. Both phenomena are a direct result of implementation of pesticide-based pest management tactics that inadvertently raise the equilibrium position of an insect pest by impeding or eliminating density-dependent control factors (Flint and van den Bosch, 1981; Norlund, 1984). Replacement pest occurrence is a long noted and discussed consequence of pesticide use. In these instances the primary pest is strongly affected by the tactic while the
replacement (secondary) pest is not. Additionally broad-spectrum insecticides are often lethal to competitors and/or biological control organisms (natural enemies) that have a role in keeping (secondary) insect pests in check (Pedigo, 2002). Likewise insect pests evolve resistance to pesticides faster than beneficial predators and parasites (Tabaskin and Croft, 1985). When broad-spectrum pesticides are employed for management of primary pests, previously non-pest or secondary pest species become problematic as a result of the elimination or reduction in natural control agents (Beers 1998; Carl, 1996; Luna and House, 1990; National Research Council, 1996). Flint and van den Bosch (1981) note that the post-World War II pesticide revolution “ushered in a whole new spectrum of previously unknown pests”. Many arthropods whose populations had been generally small or moderate became major crop pests. They attributed this to insecticide-induced mortality of natural enemies and pest tolerance to pesticides coupled with tremendous pest species reproductive capabilities. Frequently when secondary pest outbreaks occur, because natural enemies are killed by pesticides, additional and often more expensive pesticide applications must be made to achieve desired yields (Pimental, 1992).

Similarly resurgence is not an uncommon consequence of insecticide use. Resurgence occurs when a pest population, after being suppressed by pesticide treatment, rebounds to numbers greater than before treatment. Like replacement, resurgence of pest populations likely occurs as a result of the elimination of natural enemies (Pedigo, 2002).

Several apple arthropod pests have reached seriously problematic levels, according to Croft (1982), because their natural enemies have been killed or adversely affected by pesticides. Examples of this include San Jose scale, oystershell scale, European red mite, two-spotted spider mite, apple rust mite, rosy apple aphid, wooly apple aphid, white apple leafhopper and red-banded leafroller. Entomologists generally observe and indicate that the loss of natural enemies due to insecticide use is severe in many parts of the world. This is serious, according to Pimental
in that biological control by natural enemies in natural systems and agroecosystems may account for 50% to 90% of the control of a pest species while pesticides provide an additional 10% control and other factors (e.g. host plant resistance, disease and other limiting factors) the remainder.

Pesticide treatments have also been known to damage crop plants. Recommended dosages of insecticides have been reported to suppress both growth and yield of some crop plants. Pesticide drift from target to non-target crops frequently contribute to crop losses. This is particularly problematic in regions with diverse crops such as the Columbia Basin in Central Washington. Both ground and aerial application techniques are subject to drift resulting in the off-target deposition of pesticides. An estimated 50% to 75% of pesticides miss their target when aerially applied while 10% to 35% of ground-applied pesticides miss their intended target (Pimental, 1992). Off target deposition of pesticides is particularly problematic in tree fruit production, with material plumes often reaching well above the canopy. Air blast application often results in substantial drift. Davis et al. (1994) report that air-blast pesticide application accounted for only 2.6% of pesticide application in the England and Wales but gave rise to 29% of off-target incidents. Off target drift of pesticides due to air blast application remains a serious issue and a source of consternation in tree fruit production.

Likewise extensive agricultural pesticide use has also resulted in environmental contamination and the endangerment or killing of other off target animal species including livestock, honey bees, birds, fish and other wildlife (Bishop et al., 2000; Flint and van den Bosch, 1981; Fluetsch and Sparling, 1994; Hewitt and Smith, 1995; Steingraber, 1998). An estimated $30 million in domestic animals are lost to pesticide poisonings each year. Bee colony losses from pesticide poisoning approach $25 million annually. Loss in potential honey production is approximately $27 million and crop loss due to reduction in insect pollination due to pesticides may be as high
as $4 billion (Pimental et al., 1992). Ground and surface water systems have also been severely impacted by pesticide contamination (National Research Council, 1996; Weaver et al., 1990). In the Central Columbia Plateau aquifer, which lies beneath Washington and Idaho, Sampat (2000) reported that two thirds of water samples contained multiple pesticides. Pesticides are also applied to or find their way into soils where they may be toxic to macro and microorganisms such as arthropods, earthworms, fungi, bacteria and protozoa. These organisms are vital because of their roles in soil health and quality and in biogeochemical recycling of the elements vital to all ecosystems (Pimental et al. 1992).


**Public awareness and response**

Apple safety and pesticide use in particular has garnered a great deal of public focus and concern beginning with the ‘Alar Crisis’ in 1990 (National Resource Defense Council, 1989) and more recently after the issuance of “How 'bout them apples? Pesticides in children's food ten years after Alar” (Wiles et al., 1999) published by the Environmental Working Group. In 1993 the National Academy of Sciences issued a report entitled “Pesticides In The Diets of Infants and Children”. The report, which had significant influence on public awareness and subsequent regulatory activity, concluded that food tolerances for pesticides should account for children’s heightened sensitivity to pesticides and thus be lowered. Apple producing industries are
cognizant and concerned about these issues, if not from an environmental and human health perspective then from a marketing and public relations one (Barritt, 2002; Merwin and Pritts, 1993; Reganold et al. 2001; VanBuskirk, 2002). Concerning tree fruit production in Washington State, Barritt (2002) recently stated, “Undeniable trends in the apple business are reduced pesticide use and softer pest management programs. Environmental and food safety concerns are accelerating the change”. He went on to strongly urge that the central Washington apple industry should “embark on a path to become 100 percent organic” to assure domestic and international market access in an environment of changing consumer and retailer expectations relative to pesticides and food quality/safety. It has also been suggested that Washington’s apple industry seek comparative advantage in world markets via industry-wide adoption of ecologically based production practices and environmental stewardship standards (including, most notably, the significant reduction or even elimination of pesticide use) and then exploiting these production standards as a marketing tool (Mullinix, 2000).

Pimental et al. (1992) stated that most benefits of pesticide use are based on direct crop returns only. They estimated that in the U.S.A., direct pesticide use costs $4 billion and social and environmental costs another $4 billion for total direct and indirect pesticide expenditures of $8 billion for $16 billion worth of crops. Estimated actual societal net gain or loss is rarely calculated. Levitan et al., (1995) concluded, after extensively reviewing environmental impact assessment methodologies, that a comprehensive, comparative, holistic system with which to evaluate appropriate pesticide policy and farm level pesticide use was lacking and that farmers, farm advisors and policy makers would benefit from such an approach. Lee (1992) conveyed a similar assessment and said the patchwork of policies (relative to agricultural pesticide use) complicate the analysis of benefits and costs. Lack of appropriate analysis and pesticide use policy may be curtailing advancement of integrated or ecologically based pest management
systems (Ramirez and Mumford, 1995). As far as apple production is concerned it certainly seems, on the surface at least, that $300-$500 (the cost of pesticides) is a nominal and cost effective input compared to the $10,000 gross per-acre value of fresh market apples (Merwin, 1993). This ratio and the perceived return on investment (along with narrowing margins and greater risk) strongly motivate apple farmers to continue their reliance on insecticides. Pimental et al. (1992) concluded however, by saying that many costs are not completely accounted for and were they, the cost/benefit analysis would significantly reduce the perceived profitability of pesticide use in agriculture. This awareness, they say is spurring “research in environmentally sound agriculture, including non-chemical pest management’’.

The U. S. government has also recently responded to advanced knowledge of and our heightened food safety concerns about, pesticide use in agriculture. The Food Quality Protection Act (FQPA) was signed into U.S.A. law in 1996. The objective of FQPA was to improve food safety by addressing, in particular, deficiencies in the Delaney Clause of FIFRA (which set a zero-risk cancer tolerance for pesticide residues on processed foods) and the undue risk to infants and children from pesticide residues on food. Most significantly, provisions of FQPA replaced the Delaney Clause with a standard of “reasonable certainty that no harm will result from aggregate exposure to pesticide residue”. The most significant effect of this legislation will likely be the reduction of a great many pesticides tolerances (which will in turn affect their use and current pest management strategies) and the outright elimination of many pesticides, particularly organophosphates and carbamates (Pedigo, 2002; VanBuskirk, 2002; Whalon et al., 1999). In light of the unlikely re-registration of these insecticides and the fact that current fruit IPM programs rely on insecticides for suppression of pest populations, the Council on Agricultural Science and Technology (CAST) called for concerted effort and increased resources for the
development of new, local, alternative integrated pest management programs (Whalon et al., 1999).

**Arthropod pests and pesticide use in apple farming**

In the semi-arid Northwest, apple farmers, like their counterparts throughout the world have come to rely on broad-spectrum insecticides for insect pest management (Croft and Hull, 1983; Hull et al. 1983; Suckling et al. 1999; Weaver et al. 1990) though quantities applied any given season can vary greatly from farmer to farmer (Penrose et al., 1996; Wilton, 1993). According to the United States Department of Agriculture (2000) in 1999 Washington State apple growers used the following materials classified as insecticides; abamectin, azinphosmethyl, Bt, carbaryl, chlorpyrifos, clofentizine, endosulfan, fenbutatin-oxide, formetanate hydrochloride, imidacloprid, kaolin, malathion, methoxychlor, methyl parathion (now illegal), oxamyl, petroleum distillate, phosmet, pyridaben, and spinosad. To some extent these materials were applied on 99 % of Washington’s approximately 172,000 orchard acres. Some of these materials are newer, biologically derived, less broad-spectrum in their insecticidal activity and generally environmentally softer whereas the majority are older, broad-spectrum chemicals such as carbamates and organophosphates. Washington apple growers applied approximately 340,000 kg of insecticides over 172,000 acres (2.0kg/acre) during the 1999 growing season (excluding oils, thinners, kaolin and Bt). Other than oils the two most utilized insecticides by Washington State apple farmers were azinphosmethyl and chlorpyriphos. The broad-spectrum organophosphate azinphosmethyl was applied to 78 % of the apple orchard acreage in Washington, on average, 2.3 times for a total rate of 0.41 kg/acre. The primary target pest for these applications is the codling moth but it also controls several miscellaneous “secondary” insect pests. Chlorpyriphos, a broad spectrum organophosphate, is the second most widely used insecticide. It targets leafrollers and San Jose scale, and is usually only applied with oil in the
pre-bloom period. Sixty-five percent of the State’s apple acreage received an average of 1.66 applications of chlorpyriphos in 1999, a total rate of 1.0 kg per acre per year (a total of 114,046 kg applied). Azinphosmethyl and chlorpyriphos accounted for approximately 75% of insecticides applied by Washington apple growers in 1999. Washington apple growers spend between $250 and $450 per acre for insect pest control materials annually. Average direct expenditure is an estimated $350 per acre (H. Teas, 2003). This is consistent with Merwin’s (1995) estimate for eastern apple producers of approximately $375 per acre for pesticides. This cost does not include labor and application costs. In surveys, conducted by Washington State University (Jones et al. 2002) Washington apple farmers were asked to characterize their insect pest management operation. In 1989, 98.6% of respondents said they used “conventional” pest management practices, meaning they “primarily used synthetic pesticides”. In comparison, 2000 survey respondents indicated that 89.5% utilized conventional pest control tactics. In that same time period organic, transitional or mixed insect pest management practices increased from a total of 1.4% to 10.5% of respondents. Though a significant shift in pest management practices, this likely represents a response to marketing opportunities as opposed to a change in pest management/production system philosophies. When asked the value of various pest management information sources apple farmer respondents (in both the 1989 and 2000 surveys) indicated the agrichemical field staff, ie. representatives of the pesticide distribution/sales company, more than any other source as being “very” or “somewhat” important.

Between 1989 and 2000 codling moth was the most cited insect pest growers sought to control. Citations of leafroller as target pests increased tremendously, from 30.7% to 74.2%. This is, most likely due to the adoption of mating disruption and phenology models for codling moth management and subsequent reductions in and/or better-timed application of azinphosmethyl for its control. Other insects frequently cited as target of pesticide applications in 2000, but without
appreciable change from 1989, included aphids (primarily green apple- *Aphis poni*, apple grain- *Rhopalosiphum fitchii* and rosy apple- *Dysaphis pyri* -82.5 %, mullein bug (*Campylomma verbasci*)- 28.3 %), lygus bug (*Lygus lineolaris*)- 43.0 %, stink bugs (*Euchistus conspersus* and *Acrosternum hilare*)- 6.4 % and western flower thrips (*Frankliniella occidentalis*)- 5.6 %.

According to the 2000 Washington State University survey azinphosmethyl, chlorpyriphos and horticultural oils remain the most widely and extensively used pest control materials (their overall use decreased somewhat from 1986).

In the “golden days” of chemical control, a zero percent tolerance for codling moth infestation (and most other pests of apple) was expected and often achieved and consumers as well as producers have come to expect cosmetically perfect fruit (Carl, 1996). It was impossible to imagine growing apples without insecticides (Leius, 1967). However apple farmers, in the Northwest and elsewhere, are widely adopting advanced integrated pest management technologies and methodologies, such as field monitoring, pheromone traps, biological controls, mating disruption, sterile release, use of economic thresholds and degree-day models and as a result their overall insecticide use is declining (Hardman, et al., 1987; Jones et al. 2002). The perfection paradigm, however, still prevails and as such fruit farmers are still reliant on insecticides. (Merwin and Pritts, 1993). Carl (1996) suggests that current crop loss tolerances, though more realistic than zero, are still unreasonably low. He contends that 5% or higher levels of fruit damage could and should be tolerated (particularly in light of world over-production) to reduce pesticide usage and increase the chances for successful biological control. He says our general belief is that we have done enough for the conservation of natural enemies if we adhere to the use of selective pesticides and we do not over use them and encourage insectivorous species. But he went on saying, “is this really all we can do?” Carl suggests that we do not know the environmental conditions under which natural enemies thrive. He asks “what do we
know about the almost countless number of parasitoids that attack leafrollers, leafminers, aphids and other pests around the world” and says that we have a “paucity” of knowledge in this regard.

Prokopy (1991) suggested that two fundamentally different approaches to the management of orchard pest complexes can be taken. One, which has been used for the last five decades involves a comparatively harsh level of human intervention and high input of off-farm materials (even in modern IPM systems). The other approach combines modest human intervention with low-input of purchased materials and emphasizes cultural, biological, host-tree resistance and behavioral methods of pest management. Pesticide interventions are a last resort and a step taken only when all others have failed. This approach offers the potential for sustainable fruit production with minimum adverse impact on soil and water quality, and on other organisms including beneficial arthropods and microorganisms, humans and other vertebrates. Few apple farmers, he contends, endear or seek to manifest the latter approach.

From pesticide to ecologically based agricultural pest management

In recognition of the shortcomings of pesticides as a solitary or primary pest management tactic the concept of ecologically based or integrated pest control/management has emerged. Integrated pest management, or IPM as it became commonly referred to, as a comprehensive concept was first introduced around 1959. It has subsequently been refined, expanded and incorporated into most agricultural systems (Flint and van den Bosch, 1981; National Research Council, 1996; Pedigo, 2002).

The founding principles of IPM are that natural processes can be manipulated to increase their effectiveness and chemical controls should be used only when and where natural processes of control fail to keep pests below economic injury levels. IPM programs employ a variety of pest
management tactics including biological control, cultural control, autocidal control and chemical control in an integrated, multi-dimensional strategy for pest management. IPM does not preclude the use of insecticides rather it prescribes their judicious use. In IPM programs pesticide use is not based upon the simple presence of a pest but a pest density that causes damage equal to the cost of control measures; the economic threshold. Treatment timing is based upon an action or treatment threshold, the pest density at which control measures must be made to prevent crop loss that would exceed the cost of control. Treatment thresholds vary under differing conditions. As such IPM programs are information intensive. They rely on identifying, monitoring and estimating pest populations, predictive models, knowledge of pest and crop plant biology and ecology and an understanding of how the range of agricultural practices affects the full compliment of pest/crop plant species and their interactions (Beers et al. 1993; Flint and van den Bosch, 1981; Kogan, 1988; Pedigo, 2002).

Many contend that IPM in its original sense of integrated and ecologically based management has not been adopted and implemented on a large scale. It is said that the most widely used IPM strategies merely stress and result in improved pesticide usage (Benbrook, 1996; Flint and van den Bosch, 1981; National Research Council, 1996; Tette and Jacobson, 1992). They note that current day IPM programs generally still depend upon pesticides as the primary pest management tool and call for the development of systems that depend primarily on biological, cultural and other ecologically based pest management tactics (Altieri, 1994; Benbrook, 1996; Bugg and Pickett, 1998; Carl, 1996; Flint and van den Bosch, 1981; Hill et al., 1999; Kogan, 1988; Lewis et al. 1997; Maxwell, 1999; National Research Council, 1996). The latter is commonly referred to as ecologically based pest management or EBPM systems.

Lewis et al. (1997) contends that the required long-term resolutions to pest problems can only be achieved by restructuring and managing agroecosystems in ways that "maximize the array of
built-in preventive strengths with the use of therapeutics strictly as a back up to natural regulators". He suggests that we rethink the entire therapeutic approach and go beyond replacing toxic chemicals with more sophisticated chemistries and/or biologically based agents. As such Lewis et al. (1997) regards IPM (and biotechnology) as only technological extensions of the therapeutic approach to pest management that do not represent the meaningful shift in pest management strategies that he calls for. A meaningful shift he contends constitutes a comprehensive understanding and utilization of naturally occurring biological agents as well as other components of the agricultural ecosystem (in the design and management of cropping systems) that keep pests within acceptable bounds. Hill et al. (1999) supports this sentiment saying that ecological studies of agroecosystems have demonstrated great and largely untapped opportunities for knowledge intensive, bio-ecological design and management of orchard systems.

Prokopy (1994) put this same concept in other terms. He refers to the notion of "ideal Integrated Pest Management" and likens the progress toward ideal IPM implementation in orchards to climbing a 4-step ladder. First level IPM involves the use of ecologically sound multiple management tactics for a single pest class (arthropod, disease, weeds, or vertebrates). Integration in this first level involves the use of selective pesticides (chemically-based IPM) initially and then the use of non-pesticidal methods such as plant resistance, biological controls, cultural controls and behavioral controls (biologically-based IPM). Rootstock resistance to wooly apple aphid and biocontrol of leafminers are examples. Washington orchardists currently employ a fair amount of first level IPM tactics in their orchards systems. Second level IPM requires the integration of multiple management tactics/practices across all classes of pests. Third level IPM involves the integration of all management practices (pest and other) across the entire system of crop production. That is, all pest management practices for all classes of pests
must be interwoven with all horticultural practices and overall farm management. This level of IPM is relatively synonymous with the biologically/ecologically based total system approach to pest and agri-system management espoused by Lewis et al. (1997) and in essence is the ecologically based pest management concept. In fourth level IPM there is calculated and purposeful blending of concerns of all who have a vital interest in orchard crop pest management; growers, consumers, packers and processors, neighbors, regulators, researchers, etc. in addition to the aforementioned attributes of level three IPM.

It is doubtful, Prokopy (1994) says, that more than a handful of commercial orchards in the world today employ second, third, or fourth level IPM practices. Rather it is likely that most practice little more than chemically based IPM to minimize harmful effects to beneficial natural enemies. A few may be using non-pesticidal, biologically based tactics as well. This likely describes the mode of operation of the preponderance of Washington’s tree fruit orchards.

The U.S. National Research Council Board on Agriculture, at the request of the United States Department of Agriculture and the Environmental Protection Agency, investigated the need for new pest management methods (National Research Council, 1996). They called for research, development and implementation of “Ecologically Based Pest Management” (EPBM) systems that are “long-term, cost-effective, solve unmet needs, and protect human and environmental health” and that have the fundamental goals of safety, profitability and durability. They also said “future pest management systems will be based on a broad knowledge of the agroecosystem and will seek to manage rather than eliminate pests. Agricultural practices that augment natural processes that suppress pests, where available, will replace existing practices that disrupt natural processes; and these practices will be supplemented with the judicious use of biological-control organisms and products, target-specific chemical pesticides, and pest-resistant plants".
Stability (low variance in pest density over time) will be a major objective and feature of successful EBPM systems. When sufficient, diverse and effective natural enemies, pathogens and competitors of pests are present in agroecosystems, pest populations will be held in check just as they are in natural systems. Similarly Lewis et al. (1997) suggested that "long term sustainable solutions must be achieved through restructuring the system so that inherent forces that function via feedback mechanisms such as density dependence, are added and/or function more efficiently." EPBM builds upon cultural and biological approaches to pest management and pest management practices must reflect a full appreciation of the interactive webs in agricultural ecosystems and seek solutions with net benefits at the total ecosystem level. In EBPM biologically derived and/or based management methods replace therapeutic methods on the frontline of our pest management strategies and central in our pest management philosophies. Strategies will emphasis and capitalize on ecosystem strengths.

Hill et al. (1999) describes an evolution of agroecosystem/pest management approaches that consists of three overlapping stages- efficiency, substitution and redesign (ESR). Codling moth management exemplifies this concept. Prior to (approximately) 1980 Washington apple growers applied insecticide cover sprays on a calendar basis for codling moth control. With the development of the degree-day, phenology model (Beers et al., 1993) cover application became more closely and consistently timed with egg hatch and larval presence. As a result, treatment effectiveness increased and excessive, wasteful application of azinphosmethyl, or another broad-spectrum insecticide, was substantially eliminated. Thus greater efficiencies were achieved. With the adoption of pheromone-based mating disruption for codling moth the need for insecticides was reduced to supplement the primary tactic, or to treat hot spots or orchard boarders to prevent immigration. As such codling moth mating disruption constitutes a substitution of technology. Finally, mating disruption represents the creation of an opportunity
to redesign our orchards relative to the pest management strategies we employ. Croft and Hull (1983) suggest that it appears as though apple orchards may be nearing an equilibrium point of pest colonization in many areas of North America. It may be then that the time is right and there is opportunity to re-evaluate and significantly restructure our pest management strategies and philosophies for Washington apple orchards. Ecologically based pest management represents the logical next step in apple pest management approach.

A variety of compelling reasons exist for increased emphasis on the development and implementation of ecologically based pest management. A fundamental shift from therapeutic pest management strategies to a whole system, ecologically-based approach appears requisite. Future pest management strategies must be based on ecological principles and take advantage of natural components of the agroecosystem to achieve pest management within fluctuating but acceptable bounds. Cropping systems will be developed to achieve this. The National Research Council's Board on Agriculture (National Research Council, 1996), because the knowledge base to accomplish this is so limited, calls for comprehensive investment and a national research agenda to develop and implement EPBM in agriculture. They said that thus far only cursory knowledge about the biological factors that control agricultural pests has been developed, including understanding of the ecosystems in which agricultural predators and prey coexist, and that these investigations will provide an understanding of the basis for agroecosystem stability. The National Research Council Agriculture Board report lists, among others, the following as priority research areas: ecology of managed ecosystems, identification and conservation of natural resources necessary for EPBM, development of ecologically-based crop protection strategies and implementation and evaluation of EBPM.

Traditional IPM programs, though based on ecological principles, rely heavily on reductionist approaches to control single pests on single crops (Stary and Pike, 1999). The National Research
Council (1996) stressed the importance of in-situ, whole farm investigation to facilitate the implementation of EPBM strategies, which, they said, will require an interdisciplinary, whole systems approach. This mirrors the sentiment of Lewis et al. (1997) and Maxwell (1999), who stated that “there are two philosophical approaches to experimentation leading to ecologically-based pest management. The first assumes that through reductionist investigation we can develop prescriptive management tactics. The second approach relies on the study of general patterns of variations and behavior in pest communities and populations in response to manipulations”. The latter approach, he went on, identifies only general concepts, but Maxwell (1999) and others (Lewis, 1996; National Research Council, 1996; Pimental, 1992) contend that we must change our perspective from prescription or short-term seasonal solutions to concept-based, long-term, ecologically founded, sustainable ones.

**Orchard arthropod community affected by pest management strategies**

In orchards, like other ecosystems, insect population stability is correlated with 1) species diversity, 2) plant structural diversity, 3) distance from sources of colonists, 4) length of contemporary time available for colonization and 5) evolutionary time available for co-evolution between herbivores and their host plants. Trees, the ground cover, the soil, and the surrounding environment all influence arthropod diversity and stability in an orchard. Apple orchards can and sometimes do provide habitat for a wide range of insects; both r and K adapted species. The extensive use of fertilizers and pesticides probably has the greatest effects on species diversity and stability in orchard systems. Pesticides, depending on the extent of use, concentrations and selectivity may greatly reduce the number of arthropod species, favoring those with high dispersal and rapid re-colonization capabilities as well as those tolerant or resistant (Croft and Hull, 1983). Ultimately an essential prerequisite to effective ecosystem based pest management in orchards is a knowledge of all the species in the community, including pests and beneficials,
an understanding of how the kinds and abundances of species change through time as well as knowledge of interspecific interactions (Brown and Welker, 1992). Studies have documented the arthropod community in apple orchards (Brown, 1993; Hagley, 1974) and many have evaluated the effect of orchard/pest management systems on the arthropod community (Altieri et al., 1993; Beers and Brunner, 1999; Beers, 1998; Brown, 1993; Brown and Schmitt, 2001; Brown and Welker, 1992; Brown et al. 1997; Gut et al. 1995; Hull et al., 1985a; Hull et al. 1985b; Hull and Starner, 1983; Jenser et al., 1999; Niemczyk, 1997; Polesney, 1996a; Polesney, 1996b; Prokopy, 1991; Prokopy et al. 1980; Suckling et al. 1999; Trimble and Solymar, 1997; Trimble and Vickers 2000; Walters, 1973; Wishniewska and Prokopy, 1997).

Early IPM investigations often revealed detrimental effects on natural enemies of crop pests when broad-spectrum insecticides were used for pest control (Hagley, 1978; Li et al., 1992; Willson and Trammel, 1980). More recently investigators have compared the effects of various orchard pest management systems, such as organic, biodynamic, IPM, and conventional, on the arthropod community in orchards (Buban et al. 1996; Balazs et al. 1996; Ciglar, 1996; Jenser et al. 1999; Prokopy et al. 1990; Prokopy et al. 1994; Prokopy et al. 1996; Wildbolz, 1988). Brown et al. (1997) compared the use of selective pesticides and ground cover plantings with conventional pest management in orchards in four Eastern European nations and in the U.S.A. They found an increase in biological control at all sites using selective pesticide management. Epstein et al. (2001), as did Pfiffner and Niggli (1996), found that predatory ground beetles, potentially significant generalist predators of immature codling moth in mating disruption orchards, were very susceptible to broad-spectrum insecticides. Bostanian et al. (2001) evaluated the buildup of predator/parasitoid fauna to an “effective biocontrol force” in a mature orchard with a companion plant groundcover and no insecticide applications post fruit set. The percentage of undamaged fruit (from insects) in test plots was 4.8% in the first year rising to
91.7% five years later. The long-term absence of pesticides in the orchard facilitated a quicker buildup of parasitoids and less fruit damage by insect pests. They also monitored Hymenoptera and Diptera. Within four years the ichnuemonid density increased 3.7 fold, chalcidoid density 5.5 fold, proctotrupoid density 4.1 fold and tachinid density 2.6 fold in treatment plots versus 4.2, 4.1, 6.9 and 2.4 fold, respectively, in one check plot. They demonstrated that with the long-term absence of in-season insecticides and altered orchard landscapes one might expect increased predator/parasitoid fauna and decreased fruit damage over a prolonged period. Altieri et al. (1993) discussed the fact that through the transition from unmanaged to intensively managed, a dramatic decrease in diversity occurs and that generally, in pesticide free orchards a wide range of parasitoids are present. They cited a study surveying Hymenoptera in unmanaged Wisconsin and Indiana apples. In those orchards a wide range of parasitoid species were present; 102 species in Indiana and 178 species in Wisconsin. In apple orchards under mating disruption for codling moth, Beers (1998), found that some insect populations remained the same (e.g. aphids), some increased (e.g. leafhoppers and leafrollers), many secondary pests were fewer, and in several instances natural enemy populations were generally higher as compared to conventionally managed orchards. Wisnieska and Prokopy (1997) studied spiders in apple orchards under different pesticide regimes. They found all spider populations increased over time in blocks managed with reduced pesticide applications. Spiders were 2 to 3 times more abundant by the end of the growing season. They concluded that pesticides, even when applied early in the season only, had a marked long-term effect on spider populations in commercial orchards. Similarly Bostanian et al. (1984) demonstrated that spider populations in Quebec apple orchards were numerically depressed by chemical based pest management practices. They concluded that if spiders are to be included in a pest management program for summer generation control of insect pests such as obliquebanded leafroller, Choristoneura rosaceae (Harris) a scheme to allow spiders to attain maximal numbers as early in the season as possible is
required. In the Netherlands, de Reede et al., (1985) anticipated that the elimination of broad-spectrum insecticides in north-western and southern European apple orchards would cause a complex of nearly 10 leafroller species to thrive. In another study de Reede et al. (1984) found alternate (to broad spectrum insecticides), selective materials effective but also that the leafroller parasitoids *Apanteles ater* (Ratzenburg) and *Colpoclypeus florus* (Walker) as well as the mite predator *Typhlodromus pyri* (Scheuten) appeared to be less susceptible to the materials than did their hosts thus creating potential for enhanced biological control. In a subsequent experiment they detected enhanced leafroller (*A. orana*) parasitism by *C. florus* in the summer. In this experiment Dimilin application (for leafroller management) evoked an outbreak of wooly apple aphid (*Eriosoma lanigerum*) because it’s earwig predators were killed (de Reede et al. 1985).

Brown and Adler (1989) compared the phytophagous arthropod community structure in apple orchards that were representative of three management approaches; abandoned, organic and conventionally managed. All indices showed significantly greater diversity in abandoned orchards (no management interventions), intermediate diversity in organic orchards and least diversity in conventionally managed orchards. In managed orchards, communities were dominated by r-selected species and in abandoned orchards by K-selected species. They hypothesized that community structure was regulated by human-induced, environmental factors in managed orchards and by natural enemies in abandoned orchards. Brown and Welker (1992) evaluated arthropod community development in newly established apple orchards under three intensities of management. Despite the fact that all orchards in the test acquired arthropods from the same species pool they found that management approach had a significant impact on the development of the phytophagous arthropod community with insecticide use having the most profound influence by greatly reducing diversity. Pruning and herbicide use had a less obvious effect but none the less altered resources on which a portion of the community developed and therefore, they concluded, cultural practices as well as insecticide use must be accounted for in
regard to arthropod community development and composition in apple orchards. Later Brown (1993) evaluated pesticide disturbance to the phytophagous and beneficial portions of a naturally evolved arthropod community in a six-year old apple orchard. Initially there was a reduction in diversity of both the phytophagous and beneficial arthropods because of the pesticide. Fifteen months after pesticide application, diversity of the phytophagous community was numerically similar in both treatments. However, Brown noted that the pesticide-treated community was dominated by r-selected species while the control (no pesticides) population was dominated by K-selected species.

The emergence of leafrollers as the new key pest

Codling moth, a pest in nearly all apple growing regions of the world and the primary or key pest in Washington State (Beers et al. 1993), has traditionally been managed with 1-5 broad spectrum, organophosphate pesticide applications. (Madsen and Morgan, 1970; Madsen, 1984b). However, the adoption of mating disruption has reduced the reliance on conventional control methods for this key pest in many orchards (Madsen and Morgan, 1970; Alway, 1996a; Alway, 1997b).

With the utilization of codling moth mating disruption and the reduction of broad-spectrum insecticides in general, leafrollers have emerged as a serious orchard pest (Alway, 1996b; Hoyt, 1979). Similar reports emanate from other regions of the U.S. (Alway, 1996b; Brunner, 1991), British Columbia, (Madsen and Morgan, 1970; Mayer and Beirne, 1974b) and Europe (de Reede et al. 1984; de Reede et al., 1985; Gruys 1982). Walker and Welter (2001) noted that leafrollers were the secondary pests most likely to break out under codling moth pheromone programs.

Reduced broad-spectrum pesticide use is not the only cause for increased leafroller infestations (Warner 1997a). Worldwide, fruit tree leafrollers have developed resistance to organophosphate
insecticides including azinphosmethyl and chlorpyriphos (Alway 1996b; Brunner, 1997b; Croft, 1982; Lawson et al., 1997a; Reissig et al., 1986; Vakenti et al., 1984; Waldstien et al., 1999).


Whether from reduced pesticide use in orchards or increased resistance to pesticides, leafrollers in Washington orchards are assuming “premire pest status” (Knight, 1997). In orchards managing codling moth with mating disruption and reducing insecticide use in general, leafrollers have become the new key pest (Beers et al., 1993; Knight et al., 1998).

Apple leafrollers

Leafrollers (Lepidoptera: Tortricidae), both native and imported, have become a major insect faunal component of and pest inhabiting commercial apple orchards in North America (Chapman and Lienk, 1971; Mayer and Beirne, 1974b; Strickler and Whalon, 1985; Weires and Riedle, 1991). The obliquebanded leafroller, Choristoneura rosaceana (Harris) and Pandemis pyrusana (Kearfott) are the two most prevalent and destructive leafrollers in Washington apple orchards (Beers et al., 1993; Brunner, 1997b). Pandemis pyrusana was first reported as a sporadic pest in Washington orchards by Newcomer and Carlson (1952). Hoyt (1979) described the spread and establishment of P. pyrusana in Washington apple orchards during the 1970’s. Through the 1980’s P. pyrusana was observed with increasing regularity (Brunner, 1983). P. pyrusana is primarily a pest in established, bearing apple orchards (Brunner and Beers, 1990). The obliquebanded leafroller, a native and widely distributed North American species (Reissig, 1978) is most often (but not exclusively) a pest in newly planted and young orchards in Washington
Obliquebanded leafroller was once the dominant orchard leafroller species in interior British Columbia but became less prevalent in the mid 1970's (Mayer and Beirne, 1974b). It was described again as a prevalent and major pest in British Columbia apple orchards by Madsen (1984a) and again by Smirle (1993) and it is considered a major apple pest in New York (Onstad et al., 1985).

Both leafrollers are polyphagous. *P. pyrusana* has been collected from diverse wild hosts that may provide a reservoir for commercial orchard infestation. The obliquebanded leafroller occurs over a wider range of host species (50-80) in Canada and the eastern U.S. (Brunner and Beers, 1990). Apple and rose however have been described as their primary hosts (Mayer and Beirne, 1974a).

Eggs of *P. pyrusana* and obliquebanded leafroller are laid on the upper surfaces of leaves in masses of 50 to 300. It is difficult to distinguish between the young larvae of these species (Brunner and Beers, 1990). Leafroller larvae occur most often either inside a folded leaf with opposing margins connected by silk threads, between two attached leaves or under a leaf attached to an apple. When disturbed from their refuges the larvae tend to wriggle rapidly backwards and drop from their shelter suspended by a single thread (Brunner, 1991). Larvae can disburse by “ballooning” on silken threads (Brunner, 1997b; Smirle, 1993).

The life histories of pandemis and obliquebanded leafrollers are quite similar. In the Pacific Northwest these species are bivoltine. They overwinter as first, second or third instar larvae within a silken hibernaculum. Hibernacula are typically located in protected parts of apple tree scaffold branches. Young, overwintering larvae become active in the early spring as fruit buds expand. By the half inch green stage of fruit tree development (pre-bloom) nearly all have left their hibernacula. They bore onto opening buds to feed on expanding leaves and flower clusters.
These larvae are fully grown by mid to late May. Overwintering generation pupae are present from mid-May through early June. Time of appearance of overwintering generation adults depends upon spring temperatures but usually occurs from late May to early June, with peak activity in mid-June (Beers et al., 1993).

Summer generation egg hatch timing varies from year to year but maintains the same temporal relationship to peak summer adult emergence. Peak summer generation adult activity occurs mid to late August. Egg hatch begins in late August and can continue through September. The resultant young larvae (first - third instars) feed on foliage and fruit for a period and move to build hibernacula in scaffold branches in October (Brunner, 1991). Knight (2001) reports that pandemis larval densities can increase five fold between overwintering and summer generations on apple (*Malus domestica* Borkh).

Adult males have been shown to travel distances of up to 300 meters. Female moths however do not move very far and likely lay 90% of their eggs on the same tree on which they developed from larvae. Though larvae can contribute to population dispersal by ballooning, this results in a high level of mortality and is not thought to be a significant factor (Brunner, 1997b; Warner, 1996a). Brunner (1997b) offers that leafroller populations tend to come from within orchard infestations as opposed to resulting from massive invasions from external sources. Knight (2001) however, said that leafroller management in apple tends to ignore the role of extraneous orchard habitat, e.g. sweet cherry (*Prunus avium*), which allows populations of *P. pyrusana* to remain established at high levels within a given region. He suggests that effective management of a polyphagous pest such as *P. pyrusana* requires a concerted area wide effort across all potential hosts.
Both leafroller species exhibit direct and indirect damage to fruit crops. In the spring larvae web together leaves and feed in expanding flower parts and vegetative buds. As larvae mature they migrate to growing shoots and web together leaves to make shelters. Pandemis and obliquebanded leafrollers feed primarily on foliage (indirect damage) that has minimal economic impact on mature orchards. Larvae do not require fruit to complete their development and do not seem to particularly seek fruit for feeding. However it is not unusual for larvae to attach leaves to fruit or use fruit clusters as sheltered feeding sites which usually results in some level of fruit feeding (direct injury) and this is responsible for the insects detrimental impact (Beers et al., 1993; Brunner, 1991; Waldstien and Reissig, 2001).

Madsen and Carty (1977) reported that leafrollers were the insect most difficult to manage in reduced pesticide test orchards in British Columbia. Damage to fruit was consistently between 1.5 - 2.0 %. Subsequently Madsen (1984a) reported fruit damage to apple orchards exceeding 3.5%. Gruys (1982) and de Reede et al. (1985) speculated that leafroller fruit damage in European orchards might reach 10% with reduced pesticide use. Hoyt (1979) described 20% fruit loss in Washington fruit orchards from *P. pyrusana* alone. In California apple orchards, treated with codling moth pheromone mating disruption, 10 to 15 % fruit damage from leafrollers at harvest was reported (Walker and Welter, 2001). Apple cultivar seems not to be a factor influencing obliquebanded leafroller damage rates (Onstad and Reissig, 1986; Waldstien and Reissig, 2001).

The distribution of leafroller larvae and hence their associated damage is, in part, dependent upon fruit tree growth habit and size. Compact spur-type trees offer a closer association between fruit and foliage. As such they tend to have more fruit damage than standard type trees. It is not unusual for 2 - 4 times more damage to occur in the upper tree canopy than in the lower half of the canopy (Brunner, 1991). Obliquebanded leafroller is usually more evenly distributed
throughout the canopy whereas *P. pyrusana* larvae tend to occupy the uppermost portions (Brunner, 1997b). Both insects demonstrate a clumped distribution pattern within an orchard or even a tree (Alway, 1996b; Brunner, 1997b; Hansen, 1997). Zalom and Pickel (1988) found that approximately two-thirds of fruit damage caused by *P. pyrusana* leafroller in California apple orchards was in the upper regions of the canopy.

Leafroller control in the Pacific Northwest and elsewhere has been and continues to be accomplished primarily with the use of conventional synthetic broad-spectrum insecticides. Because obliquebanded leafroller and *P. pyrusana* life cycles are essentially the same, separate control measures have not been necessary. The insecticide of choice has been the organophosphate chlorpyrifos. It is recommended to target the overwintering larvae just after they leave their hibernacula with a delayed dormant oil/chlorpyrifos spray. Optimum timing is at the half inch green stage of apple development (Brunner, 1991; Brunner, 1997b; Olsen et al., 1987; Waldstien and Reissig, 2001). To avoid disruption of integrated mite management and to minimize resistance development, later season broad-spectrum insecticide applications are not recommended. However, in season azinphosmethyl applications for codling moth have provided some levels of leafroller control. Brunner (1997b) recommended chlorpyrifos or encapsulated methylparathion treatment for summer generation leafroller when populations exceed 5% shoot infestation. After the restriction of chlorpyrifos to the pre-bloom period and the elimination of methylparathion as an insecticide available for use on apple the bacterial insecticide *Bacillus thuringinesis* (Bt) is most often used to control late spring (overwintering larvae) and summer generation leafroller populations. Bt can also be used for control of overwintering larvae (Knight, 1997). Other management tactics have been explored or are considered to have potential (Anderson and Elliott, 1982; Brunner, 1997a; de Reed et al., 1985; Evenden et al.,
Biological control of leafrollers is also considered to have potential. One leafroller parasitoid of particular interest is the eulophid wasp *Colpoclypeus florus* (Warner, 1995, Brunner, 1991). Another parasitoid wasp that has potential to contribute to leafroller biocontrol is *Apanteles* sp. (Braconidae). Additionally tachinids (Diptera: Tachinidae), parasitic flies, are a large and potentially valuable group of parasitoids for leafroller biocontrol (Beers et al. 1993). Miliczky and Calkins (2002) have also investigated spiders (Araneae) as potential predators of apple leafrollers.

**Biological control strategies and arthropod agents of biological control**

Every organism is affected by natural suppressive factors, including natural enemies, operating in its ecosystem (Flint and van den Bosch, 1981). Biological control is an important element of integrated pest management and key to an ecologically based pest management strategy. It employs the manipulation of that pest’s natural enemies; disease causing microorganisms, predators and parasites to kill outright, weaken and contribute to premature death or compromise reproductive capabilities. Control by natural enemies is inexpensive, permanent and non-disruptive of other ecosystem elements (Flint and van den Bosch, 1981; Hagler, 2000; Pedigo, 2002). Predation and parasitism are two key biological control factors. They have comparable regulatory effect upon insect pest (prey) populations and as such a great deal of predation ecological theory has been developed with parasitism in mind (Price, 1997). In nature there is a balance between pest populations of arthropods and their natural enemies. In managed ecosystems that balance is disturbed. But by manipulating environmental factors balance can be restored and more permanent, effective pest suppression achieved (Flint and van den Bosch,
McMurty et al. (1981; McMurty et al., 1995). McMurty et al. (1995) describe biological control as the most acceptable long-range control tactic for incorporation into long-range pest management programs. The goal of most biological control programs is to establish a self-sustaining system. The theoretical mechanism for a self-sustaining system is based on food supply for and reproductive capability of the natural enemy. As pest populations increase food supply for the natural enemy increases and as the natural enemy population increases, an increasing proportion of the pest population is destroyed. Ultimately natural enemy populations also decrease as the prey/host population decreases and a fluctuating cycle occurs. In successful biological control, fluctuations occur within a range that maintains the biological control mechanism and, in an agroecosystem, within acceptable crop damage/loss levels (Pedigo, 2002; Southwood and Way, 1970).

Biological control practices are generally grouped into three categories 1) classical biological control or introduction 2) conservation and 3) augmentation (Beers et al. 1993; DeBach, 1964; Flint and van den Bosch, 1981; Hagler, 2000; Johnson and Wilson, 1995; Mills, 1992; Norlund, 1984; Rabb et al., 1976; Pedigo 2002). Rabb et al. (1976) suggest it is unlikely in agroecosystems that a single natural enemy will solve a pest problem. Therefore techniques should be viewed as potential inputs into a management system in which each input serves a unique control function in an integrated approach.

The classical biological control strategy is applicable to exotic or introduced pests and has been attempted for a variety of pests around the world (Greathead and Greathead, 1993). The basis for this practice is the identification of natural enemies of the pest in its native habitat and introduction of them into the pests' new location (Beers et al. 1993; DeBach, 1965; Flint and van den Bosch, 1981; Johnson and Wilson, 1995; Pedigo 2002). Both successful and failed classical
biological control attempts are reported (Messing and AliNiazee, 1985; Nafus, 1991; Nechols et al., 1995).

Conservation of natural enemies comprises the most widely practiced form of biological control. The objective of conservation is to protect and maintain existing populations of natural enemies in the agroecosystem. The practice implies the modification of environmental factor(s) that are adverse to beneficials thus favoring the beneficials and disfavoring target pest species (Stary and Pike, 1999). Crop production practices (e.g. mowing, pesticide application timing, choice of pesticide materials, reduced rates of pesticide application) are altered to protect predators and parasitoids. Conservation of natural enemies requires in-depth knowledge of the natural enemy community including species present, population, phenology and impact on pest species (DeBach, 1965; Pedigo, 2002). Reduced pesticide application and the use of selective pesticides in apple orchards have repeatedly demonstrated the possibility for the conservation of natural enemies (Biddinger et al., 1994; Bostanian, 2001; Brown and Welker, 1992; Brown et al., 1997; Epstein et al., 2001; Li et al., 1992; Mills, 1992; Niemczyk, 1997; Trimble and Solymar, 1997; Trimble and Vickers, 2000; Van Driesche et al., 1998). Mills (1992) stated that “biological control conservation in pome fruit orchards is important in the context of both indigenous and imported natural enemies”. He went on to say that it is clear management practices have a strong influence on natural enemy populations in fruit orchards. He also said, modified orchard management practices such as the use of selected insecticides and nectar producing ground covers can play a very important role in conservation of indigenous and imported natural enemies and that the naturally occurring biological control of secondary pests (e.g. leafrollers) in fruit orchards in the west is testimony to the importance of natural enemy conservation.

Finally, augmentation involves activities that are designed to increase the numbers or effect of existing natural enemies. This is commonly achieved by releasing additional natural enemies
into the system or by modifying the environment to promote greater numbers and/or
effectiveness of natural enemies (Beers et al., 1993; DeBach, 1964; Flint and van den Bosch,
1981; Mills, 1995; Pedigo, 2002; Stary and Pike, 1999). Augmentative releases are expected to
result in temporary suppression only as opposed to significantly changing the pest equilibrium
level. As such they are thought of as “biotic insecticides” (Johnson and Wilson, 1995; Pedigo,
2002).

Augmentative releases therefore must be made periodically and are considered either inundative
or inoculative (Beers et al, 1993; DeBach and Hagen, 1964). Inundative releases depend upon
the rearing of massive numbers and widespread distribution of natural enemies. The release is
expected to result in immediate suppression of pest populations with little or no benefit from
their progeny. Though arthropod natural enemies have been used successfully in inundative
releases (Oatman and Platner, 1971; Oatman, 1978, Oatman et al., 1977) many other attempts
have not been successful. Lack of success is generally attributed to insufficient coverage of the
area affected by the pest or to environments not supportive of the numbers released (Pedigo,
2002). Cossentine and Jensen (2000) discuss an example of parasitoid augmentation to control
codling moth. Mills (1995) discusses a similar strategy for both codling moth and leafroller.

Conversely, in inoculative releases, it is the progeny of the released natural enemies that are
expected to have the greatest impact on pest populations. Lawson et al., 1997b and Maier, 1993
reported on the inoculative releases of parasitoids for management of apple leafroller and
leafminer respectively.

Norlund (1984) said that it is obvious that the techniques of augmentation and conservation
overlap and that the division is only the theoretical basis of whether one seeks to increase or
maintain a population that can be helpful in visualizing various biological pest management
strategies. He suggested that it might be more useful and reduce confusion to classify biological pest management tactics as follows:

1. Importation.

2. Periodic releases.
   a. Inundative.
   b. Inoculative.

3. Environmental manipulations.
   a. Provision of alternate, factitious, or non-viable hosts or prey.
   b. Use of semiochemicals to improve the performance of entomophages.
   c. The provision of various environmental requisites, such as food or nesting places.
   d. Modification of cropping practices to favor entomophages.

The insect agents of arthropod biological control are either pathogens, nematodes, predators or parasitoids. Typically predators are primarily classified by some taxonomic affiliation while parasitoids because of their great number and diversity are generally categorized by the hosts they parasitize and where their offspring develop (Strand and Obryck, 1996). It is not unusual for two or more natural enemies to work in concert to provide control of a pest (Beers et al., 1993; Flint and van den Bosch, 1981; Pedigo, 2002). Beers et al. (1993) list the following as desirable characteristics of natural enemies: good biological control agents are adapted to the pest and preferentially specialize on it; they do not interfere with other biocontrol agents; they
reproduce rapidly; they are suited to the climate and are in synchrony with their host or prey; and they can find their host or prey at relatively low densities.

Predators are free-living organisms that feed upon and devour other prey animals. The most important predators in agricultural biological control have been insects. Predator insects may attack eggs, immature or adult stages and require more than one prey individual to reach maturity. The predatory instinct generally characterizes both immature and adult stages of predator species. Predation involves the interactions of prey and predator in time and space. The habit of predation is common amongst insects and nearly all orders have important predatory species. (Gullan and Cranston, 1994; Pedigo, 2002).

The other classification of entomophagous insect exploited in insect biological control programs are parasitoids. Insect parasitoids have long been a subject of study by entomologists and ecologists (Mills, 1992). An abundance of literature on the ecology, behavior and evolution of insect parasitoids exists and it is often difficult to cleanly separate behaviors from mediating physiological processes (Fisher, 1986; Waage and Greatland, 1986). Most insect pests have one to several parasitoid species, referred to as a parasitoid complex, that attack them (Mills, 1992). Most parasitoids are quite specific and will parasitize only a few or very closely related host species (Beers et al., 1993).

The intricacy of the insect parasitoid - host relationship is fully appreciated (Fisher; 1986; Grenier, et. al., 1986; Webb and Dahlman, 1986). Insect pest management specialists realize the need to understand the basis and mechanics of the complex relationships exhibited by insect parasitoids and their hosts. As such over the last 40 plus years much emphasis has been placed on investigation into and gaining an understanding of various aspects of parasitoid - host interactions (Fisher, 1986). One of the significant impetuses behind this is the potential for
expanded use of insect parasitoids as agents of biological insect pest control (Lewis, 1986). Indeed parasitoid insects have been used more frequently in biological control than any other kind of agent (Pedigo, 2002). Their effective and expanded utility necessitates that we, as R. C. Fisher states (1986), “take account of the full... host- parasitoid relationship...”.

Insect parasitoids are a distinct class of parasites distinguished by the fact that they appear as any other parasite in the early stages of parasitism but later kill their hosts and live as free adults that must in turn locate suitable hosts for reproduction (Vinson, 1976). And unlike other parasites, parasitoid hosts always perish in the proposition (Fisher, 1971, Vinson and Iwantsch, 1980a). They are also distinguished from other parasites in that a somewhat limited number of progeny develop in association with a given host and only one life stage is present within the host at any given time (Vinson and Iwantsch, 1980a).

Parasitoids are incredibly abundant and diverse components of ecosystems. The parasitic Hymenoptera may number more than 1 million species. Some families of parasitic Hymenoptera probably contain more species than the total number of vertebrate species combined (Strand and Obryck, 1996). On a world wide scale the numbers of insect parasitoids can only be guessed but it is estimated that over 36% of the identified insect species are parasites on animals and over 90% of those are insect parasitoids (Lewis, 1986). Or as Stoltz (1986) put it, “One in every 10 animal species is a parasitic insect and most are parasitoids”. Most research has been conducted on parasitoids in the order Hymenoptera. Other parasitoid containing orders include; Strepsiptera, Diptera, Coleoptera, Neuroptera and Lepidoptera (Lewis 1986, Vinson, 1976). Hymenoptera and Diptera orders predominate (Strand and Obryck, 1996). Ichneumonidae, Braconidae and Pteromalidae are the families with the greatest numbers of parasitoid species. Tachinidae (the parasitoid flies) is one of the most parasitoid species rich groups of the Diptera.
Parasitoids are often effective biological control agents because 1) survival is generally good, 2) generally only one host is required for complete parasitoid development, 3) parasitoid populations can be maintained at low pest levels and 4) most parasitoids have a narrow host range which generally results in good numerical response to host density. Disadvantages include 1) synchronization of the host and parasitoid, 2) host searching ability may be greatly limited by weather or other factors 3) only females search and 4) often the best searchers lay few eggs (Pedigo, 2002).

Various parasitoid-host relationships have been observed and described. Insect parasitoids are usually categorized in terms of the hosts they parasitize or where their offspring develop. Species that oviposit and complete their development in the host egg stage are referred to as egg parasitoids. Those attacking other life stages are referred to as larval, pupal or adult parasitoids respectively. If parasitoid eggs are laid in one host stage but parasitoid development is complete in another then they are described using those two stages (for example an egg-larval parasitoid). Parasitoids that parasitize insects in immature stages are referred to as proteleanparasites. Typically only one host life stage is attacked (Stehr, 1973; Strand and Obryck, 1996; Vinson, 1976). Hosts are usually found by female adults who then lay their eggs directly on or into the host. Others lay their eggs near the host. The latter become parasitic when the eggs hatch and the mobile larvae migrate to the host, gain entrance and internally feed or they may simply consume the host externally. Parasitoids are commonly classified according to where their progeny feed. Endoparasites are those species that develop within hosts while those developing externally are called ectoparasites. Some adult parasitoids feed on hosts by drilling holes (with their ovipositor) in hosts and consuming humoral substances. Some species, exhibiting this behavioral characteristic feed and oviposit on two, separate host species (Strand and Obryck, 1996).
Those parasites that produce only one progeny per host are referred to as solitary parasitoids. Gregarious parasitoids, on the other hand, are those producing more than one progeny per host (Salt, 1968; Strand and Obryck, 1996; Vinson and Iwantsch, 1980a).

If a parasitoid’s host continues to grow after parasitism the parasitoid is called a koinobiont. If the host ceases development upon being parasitized the parasitoid is called an idiobiont. Ectoparasitoids that permanently paralyze (usually with venom) as well as egg and pupal endoparasitoids are usually idiobionts. In contrast endoparasites of larvae and adults are usually koinobionts (Strand and Obryck, 1996). Certainly the substantially varied descriptions of insect parasitoid-host relationships speaks to the potential complexities of the biological, physiological and ecological interactions of parasitoids and their hosts.

The process of successful parasitism has been divided into 5 steps: 1) host habitat location, 2) host location, 3) host acceptance, 4) host suitability, and 5) host regulation. The first three steps can be combined into the subject of host selection. (Jones, 1986; Van Alpen and Vet, 1986; Vinson, 1976; Vinson and Iwantsch, 1980a). Host location ability is a critical quality of a biological control agent. The impetus for a parasitoid to initiate host searching is unknown. What directs host location is not entirely clear either (Jones, 1986). Some suggest that host search behavior is an innate activity released by the physiological status (e.g. maturing eggs) of the insect and that subsequent searching/host location behavior is a random phenomenon (Jones, 1986; Vinson, 1976). Random searching may be involved in host location for many parasitoid species. However many insect parasitoids appear to be guided to their host by chemical and physical cues which elicit a series of directed responses by the female and that consequently serve to restrict the area and habitat searched as well as the species of host located. Chemicals and chemoreception, emanating from a plant or insect host are now considered to play the major role in almost all aspects of parasitoid host selection (Salt, 1976; Strand and Obryck, 1996; Van
Alpen and Vet, 1986; Vinson, 1976). An increasing refinement of these factors may be exhibited in more host specific parasitoid species (Aldrich, 1995; Jones, 1986; Strand and Obryck, 1996; Vinson, 1976).

Antennae, ovipositors and tarsi have generally been accepted as functioning in the perception of chemical cues leading to the host (Jones, 1986; Vinson, 1976; Tumlinson et al., 1993). Jones (1986) suggested that in regard to host locating, parasitoids do not necessarily respond definitively and serially to chemical cues emanating from habitat, host damage, hosts etc. Rather they may respond to accumulated chemical cues. Thus their response at any given time is dictated by the sum total of all cues impinging on their chemoreceptors. Harris and Foster (1995) stated that even the most apparently simple and straightforward of chemically-mediated host location behaviors is complex and probably involves a multitude of inputs.

Host marking enables parasitoid females to discriminate between those hosts already parasitized from those not parasitized (Vinson and Iwantsch, 1980b) and marking appears very common among Hymenoptera (Vinson, 1976). Marking may occur in two general ways; externally or internally. External marking is accomplished with pheromones while internal markers are the result of changes in the host after parasitoid oviposition. External markers tend to be ephemeral while internal markers endure through the development of the parasitoid (Strand 1986; Vinson, 1976).

The key factor that influences parasitoid success (e.g. reproductive strategies) is host quality. It is known that certain host stages, density and nutrition for example, will be more suitable than others for a given parasitoid (Beckage and Riddeford, 1992; Slansky and Scriber, 1985; Vinson and Iwantsch, 1980a). This is accentuated when hosts deviate from optimum size and age. Reduced quality often results in a decline in progeny survival and adult size. Some parasitoids
seem affected by excess resource and exhibit sex ratio shifts as a result. Additionally, morphological alterations have been correlated with host size (food supply) (Strand 1986; Vinson, 1985). Nutritional deficiencies may lead to pre-emergent mortality, unsuccessful emergence, reduced fecundity, reduced longevity, adversely affect parasitoid size, and alter the duration of parasitoid development (Vinson and Iwantsch, 1980b). Host diet may be unsuitable for the parasitoid. Many factors have been found to influence nutritional suitability of hosts. These included nutrient level and quality, the presence and levels of accessory growth factors, host diet and genetic makeup (Vinson, 1985; Vinson and Iwantsch, 1980a). Development of the immature parasitoid frequently spans several host instars. As such the parasitoid may impose a constraint(s) to appropriately prolong host development (Slansky, 1986; Strand and Obryck, 1996; Vinson and Iwantsch, 1980b).

Parasitoids induce multiple, often species specific, biochemical and developmental effects in their hosts that manifest in extreme pathological changes (Strand et. al., 1986). Many such pathologies are mediated by parasitoid secretions that influence host physiology and thereby create a hospitable environment for the parasitoid. It appears that parasitoids secrete an array of growth regulating substances such as ecdysteroids, juvenile hormone like molecules and indole acetic acid. Parasitoids also secrete peptides and proteins as well as hemocytes into their hosts' hemolymph. The ultimate role of these and other potential regulatory secretions are under investigation. (Beckage, 1990; Fuhrer and Willers, 1986; Vinson et. al., 1994).

Parasitoid venom glands secrete substances capable of affecting host physiology and behavior. Many such venoms are paralytic or at least transiently so (Piek et al., 1974; Stoltz, 1986; Zlotkin, 1985). Functionally host paralysis is thought to reduce the mortality of ectoparasitoids by lessening the ability of the host to remove parasitoid eggs or to reduce superparasitism by making parasitized hosts less obvious (Vinson, 1985). Some venoms may have other important

Ectoparasite venoms, contrastingly, act to immediately paralyze hosts or act more subtlety as an “arrestment factor” that allow the host to continue feeding until the next larval molt. Another form of chemically induced arrestment causes degeneration of host embryos (Beckage, 1990).

Parasitoid virus’ (polydnavirus) and virus like particles have been demonstrated to operate in host regulation as well. Because the virus particles are invariably observed in endoparasitetic wasp species they are considered an integral component of the parasitoid life cycle (Schmidt and Fedderson, 1989; Stoltz, 1986; Vinson et al. 1994). It is speculated that these viruses and virus like particles facilitate some sort of induced immunosuppression or that they may alter the nutritional or hormonal balance of the host. It may be that several viral - mediated activities are required for successful parasitism (Beckage, 1990; Schmidt and Fedderson, 1995; Stoltz, 1986). It is also hypothesized that in some species the polydnavirus acts in conjunction with parasitoid venoms. It may be that venom is required for polydnavirus activity (Beckage, 1990; Schmidt and Fedderson, 1989; Stoltz, 1986).

Insect parasitoids also exhibit a high level of endocrine interaction with their hosts. This contributes to the achievement of optimal growth and development and the synchronization of the parasitoid life cycle with that of the host (Webb and Dahlman, 1986). Synchronization of parasitoid development with that of the host (and vice versa) have been repeatedly demonstrated (Fisher, 1971). To be an effective biocontrol agent synchronization is critical (Beers et al., 1993; Pedigo, 2002). Commonly, parasitoids develop slowly in young hosts and rapidly in older ones. Parasitoid hosts may in fact be induced to delay development or to proceed developing without delay. In some instances host developmental changes are induced by the developing
parasitoid(s) while in other instances stinging alone will suffice (Lawrence, 1986; Vinson and Iwantsch, 1980b).

A variety of hormones that regulate insect growth and development are transported in the hemolymph and since many parasitic insects live in the host’s hemolymph it is reasonable to assume parasitoid exploitation of host hormones (Lawrence, 1986). Parasitoids, relative to endocrine communication with their hosts, have been placed into two categories. Conformers are those that depend directly on host hormones or indirectly via hormonally triggered changes in host physiology to synchronize their growth and development with that of the host. In contrast, those that interfere with their hosts hormonal system and/or produce hormonally active substances that cause the host to exist in the most beneficial state have been referred to as regulators (Lawrence, 1986). Beckage (1990) states that host conformers, which respond developmentally to host hormones, and host regulators, which induce drastic alterations in host hormone titres and metabolic pathways, probably represent two points along a continuum of host-parasitoid endocrine communications and manipulation. While some species are conformers and others regulators there are yet others that utilize both strategies (Beckage and Riddeford, 1992; Lawrence, 1986; Webb and Dahlman, 1986).

Hosts exert defenses to parasitoid exploitation and parasitoids demonstrate counter responses (Gotz and Bowen, 1995; Salt, 1968). Early views held that insect blood cells reacted to foreign bodies but not to their habitual parasites. That is now known not to be the case. Rather insect parasitoids have the means to resist and/or actively prevent insect host defense reactions from being effective (Fisher, 1986). Insect hosts exhibit varied and well developed defense reactions to parasitoids (Lynn and Vinson, 1977; Rizki and Rizki, 1984; Stoltz and Guzo, 1986). Cellular encapsulation and nodule formation by host hemocytes are well documented. Likewise parasitoid insects have developed various means to reduce the danger of succumbing to host
defense reactions. It is reasonable to suggest that parasitoids and their hosts coexist in a labile and dynamic equilibrium in this respect (Gotz and Bowen, 1995).

Parasitism is a unique form of symbiosis. Regardless of whether an insect parasite is an ectoparasitoid or endoparasitoid they exhibit high levels of nutritional, hormonal, physiological and behavioral interaction with their hosts (Beckman, 1990; Lawrence, 1986). It is imperative to further investigate the interactions and relationships between parasitoids and their hosts if the full potential and exploitation of insect parasitism for biological insect pest management is to be realized (Beckman, 1990; Fisher, 1986).

Habitat management and biodiversification in orchards for enhanced biological control

Norlund (1984) points out that environmental manipulations are used to augment natural enemy populations and activity. This strategy generally involves utilizing the crop or surrounding vegetation as a field insectary to increase natural enemy numbers or make them more efficient. Examples are common and include providing sources of alternate, supplementary or complimentary herbaceous or animal foods, enhancing refugia, nesting sites, overwintering sites, and modifying climates (Flint and van den Bosch, 1981; Norlund, 1984; Pedigo, 2002, Bugg and Picket, 1998). Cover crops in orchards have been and are currently used for such purposes and investigations into such ensues (Altieri, 1994; Altieri and Nickolls, 1999; Bugg and Waddington, 1994; Mills, 1992; Nickolls and Altieri, 2001).

Habitat management (modification of agroecosystem biotic and abiotic features) for the conservation and augmentation of natural enemies is receiving much attention. It is aimed at designing and constructing a “phytocenotic architecture” dominated by plants that support populations of natural enemies and is achieved by a variety of means and may occur in or about
the agroecosystem including manipulating the vegetation of field margins and by managing the species composition and density of plants in ditchbanks, hedgerows, windbreaks and other shelterbelts (Altieri, 1994; Gross, 1987; Stary and Pike, 1999). Similarly, within field plant diversity can be manipulated by designing polycultures of various temporal and spatial crop/plant arrangements (Altieri and Letourneau, 1982).

Agricultural system biodiversification is of great interest because:

1. Modern, monoculture agriculture approaches result in lack of biodiversification and ecological stability and buffering capacity in the agroecosystem (Altieri and Letourneau, 1982; Stary and Pike, 1999; Tedders, 1983) that invites and supports epidemic pest infestation (Norlund, 1984; Tedders, 1983).

2. Ecologists contend that diversification and ecosystem stability are interrelated. Though debated (Sheehan, 1986) it is generally assumed that increased diversity fosters stability. Conversely, the lack of diversity results in great instability, thus, requiring substantial intervention (e.g. regular epidemic pest attack and the required use of pesticides), (Altieri, 1994).

Ultimately habitat manipulation or management is a means or mechanism to achieve biodiversity and hence system stability (Altieri, 1994; Bugg and Pickett, 1998). As such, Bugg and Pickett (1998) contend that habitat management is conceptually distinct from other categories of biological control but that in practice it may interrelate to them. Habitat management, they say, may be used to support classical, augmentative and conservation of natural enemies.

Nickolls and Altieri (2001) suggest that expansion of monoculture perennial cropping systems (in California) has resulted in a decrease in abundance and activity of natural enemies of crop
plant pests due primarily to the disappearance of the plants and habitats that provide natural enemies with critical sources of food and refugia. They, as do others (Stary and Pike, 1999) suggest that one tactic (in addition to more judicious use of pesticides as discussed previously) to reverse the decline in natural control agents is to design and maintain orchard floor habitats or otherwise diversify the flora of the agroecosystem including surrounding environs for natural enemies. Undoubtedly groundcover within an orchard and vegetation adjacent to the orchard can influence interactions between beneficial arthropods and orchard pests (Prokopy, 1994). Tedders (1983) said that for deciduous tree crops, interplanting with other crops and cover crop plantings may have the broadest potential as a diversification/habitat management tool to affect beneficial elements within the agroecosystem and enhance pest control. As the focus of research it has been fairly consistently demonstrated that mixing certain plant species in with the primary plant host (crop) of a specialized herbivore insect (pest) results in a lower abundance of the specialized herbivore species (Altieri, 1994; Corbett, 1998). Stary and Pike (1999) as well as Thrupp (1996) offer that activities such as development of biocorridors and biocenters, heterogenous crops and crop structuring, polycultural crop rotation, intercropping and cover crops support and increase beneficial insect diversity and that success of biocontrol agents is commonly linked to habitats, alternate hosts and abiotic factors. Corbett (1998) however points out that in some cases vegetational management leads to a decrease in the abundance of natural enemies. Bugg and Pickett (1998) indicated that it is equally important to recognize that habitat modification is likely to affect a broad spectrum of indigenous and introduced natural enemies which could result in generalist predators interfering with the activity of a key parasitoid. Likewise vegetational diversity can aggravate pest problems by allowing them to build up on one plant species then disperse to another or by harboring complimentary food sources (prey) that discourage natural enemy dispersal to pest infested crop plants (Bugg, 1992; Merwin, 1995). Thus, Corbett (1998) said “understanding how the consequences of increasing vegetational
diversity can vary so dramatically is a major challenge in developing vegetation management systems for natural enemy enhancement. In general, increased plant diversity is believed to stabilize community parameters but not population parameters, thus say Bugg and Pickett (1998), "this suggests that the artful management of biodiversified systems may ... favor the principle economic "target species", and that multiple economically useful species should be employed in such systems, to ensure overall success. Economically useful species could include those providing multiple benefits". For example legumes are recognized as "stabilizing crops" used to improve soils and crop yields and to increase diversity of beneficials (Stary and Pike, 1999).

Farms with dominant perennial crop components, such as orchards, are considered semi-permanent ecosystems, more stable than annual plant systems, characterized by greater structural diversity and generally possessing greater potential for establishment of biological control agents especially when understory plant diversity is encouraged (Altieri, 1994; Huffacker and Messenger, 1976; Prokopy, 1994). Generally it is more difficult to achieve biocontrol in annual monocultures (Stary and Pike, 1999) but annual polycultures have been demonstrated to support a lower herbivore load than monocultures (Altieri, 1995; Bugg and Pickett, 1998; Letourneau and Altieri, 1983). This result is likely due to more stabilized natural enemy populations from an enhanced ability to persist because of the greater availability of food sources and microhabitats (Altieri, 1994).

Agroecologists have long held that plant diversification can affect arthropod densities and lead to reduced phytophagous arthropod incidence (Bugg and Pickett, 1998; Southwood and May, 1970). Many studies have shown that it is possible to stabilize insect communities in agroecosystems via the design and construction of "vegetational architectures" that support populations of natural enemies or have direct deterrent effects on pest herbivores. These studies
suggest that the more diverse the agroecosystem and the longer it remains undisturbed (sans pesticides for example) the more internal links develop to promote greater insect stability. This stability depends upon trophic diversity and on the density-dependent nature of the trophic levels (Altieri, 1994). Andow (1991) reviewed 209 published studies about vegetative biodiversity and arthropod herbivores in agricultural systems and determined that fifty-two percent (52%) of the 287 species studied were found to be less abundant in diversified systems. Only 15, or three percent (3%) exhibited higher densities.

The mechanisms by which or that are involved in agricultural diversification leading to reduced pest populations are poorly understood (Sheehan, 1986). Four main ecological hypotheses have been offered to explain lower pest population loads in diversified (multi-species) plant association:

1. Associated Resistance – ecosystems in which plant species are intermingled possess an associated resistance to herbivores in addition to individual plant species resistance. Mixed vegetation is thought to result in;

   a. The stratification and increased complexity of the canopy that reduces pest habitat and increases beneficial habitat. Additionally the complex architecture, and microclimates impedes pest attack.

   b. An alteration of the chemical environment; many host plants signal pests via chemical cues, therefore pest identification of host plants is disrupted by increases complexity of the chemical environment.

   c. The creation of varying microclimates disfavors pest attack.
2. Natural Enemies – There is a greater abundance of natural enemies in mixed vegetation agroecosystems than in monocultures. Predators tend to be polyphagous with broad habitat requirements. Therefore:

a. Vegetative diversity provides greater prey and habitat diversity; predators can exploit a wider array of herbivores that become available in different microclimates and at different times.

b. Specialized predators are less likely to fluctuate widely because the more complex environment provides refuge for and a means of escape for prey. Thus, prey avoid complete elimination and a population of predators can be supported.

c. Diverse flora offers the satisfaction of other predator and parasite requirements such as pollen and nectar.

3. Resource Concentration – insect populations can be affected by the concentration and spatial arrangements of host plants.

a. Many herbivores are more likely to find and remain on hosts that are growing in dense or nearly pure stands and that are providing concentrated resources and monotonous physical conditions.

b. In diverse systems the visual and chemical stimuli from host and non-host plants affects both the rate of colonization of herbivores as well as their behavior.

c. When the relative resource concentration is lower insects approaching a habitat will have greater difficulty locating a host plant.
4. Plant Apparency – monocultures render host plants more apparent chemically and physically.

a. Crop plants grown in monoculture have inadequate qualitative physical and chemical defenses.

b. They evolved these defenses in wholly different (diverse) environments.

(Altieri and Letourneau, 1982; Altieri, 1994, Risch et al., 1983).

These hypotheses, particularly the enemies hypothesis, have been the focus of experimental and agroecosystems design work. But Sheehan (1986) says one cannot rule out the ability of natural enemies to limit herbivore populations in many situations. He therefore has questioned, in particular, the natural enemies and resource concentration hypotheses relative to the efficacy of specialist natural enemies and proposed that enemy foraging behavior and population dynamics may be viewed in terms of the concentration of both victims and of victim-containing vegetation instead. Crop diversification may, he said, reduce enemy searching efficiency and destabilize predator/prey interactions. Specialist enemies important in biological control programs may be particularly sensitive to vegetation texture and as such pest control by specialist enemies may be more effective in less diverse ecosystems if the concentration of host plants increases attraction or retention of the natural enemy. He suggests that in consideration of such responses by specialist enemies to prey concentrations, alternate predictions about habitat diversification and natural enemies effectiveness in agroecosystems should be investigated. Southwood and May (1970) entertained but did not argue or support the notion that greater habitat diversity does not impart or increase stability. Russell (1989), reported that evidence generally supports the natural enemies hypothesis and suggests that it and the resource concentration hypothesis are complimentary mechanisms in reducing numbers of herbivores in diverse cropping systems.
Certain plants, mostly in the families Apiaceae, Leguminosae and Compositae, appear to play an important ecological role by harboring and supporting a complex of beneficial arthropods that contribute to pest suppression (Altieri, 1994; Stary and Pike, 1999) and the majority of habitat manipulation strategies employ them individually or in combination. Most studies in orchards have explored the manipulation of ground cover vegetation and resultant effects on insect pests and their associated natural enemies. Generally orchards (including apple) with diverse floral undergrowth (particularly of the kinds of plants noted above) exhibit lower incidences of insect pests because of increased predator and parasitoid presence and efficiency (Altieri and Schmidt, 1985).

To affect insect population dynamics via habitat manipulation one must consider spatial, temporal and varietal features of the cropping system and take into account local variations in things such as climate, geography, crops, local vegetation, inputs and pest complexes (Altieri, 1994; Litsinger and Moody, 1976). Altieri and Letourneau (1982) said that animal diversity has been correlated with aspects of plant diversity and that it "seems logical" that a greater variety of plants in an agroecosystem would lead to a greater variety of herbivorous insects in that ecosystem. They conveyed that both plant species and plant structural diversity have been found important in determining insect species diversity and offer the following hypotheses, based on ecological theory, to account for this:

1. Heterogeneity hypothesis: Complex crop habitats support more species than simple habitats and as such, architecturally complex plant species and heterogeneous plant associations with greater biomass, food resources variety and temporal persistence have more associated insect species than do simpler habitats.
2. Predation hypothesis: In rich plant associations increased abundance of predators and parasites reduces prey populations and concomitantly increases competition amongst herbivores. This should allow the addition of more prey species which in turn support new natural enemies.

3. Productivity hypothesis: Polycultures yield more (total biomass) than monocultures. Greater productivity (food resources), which sets the upper limit to the number of species in a crop community, can result in greater diversity.

4. Stability and temporal resource-partitioning hypothesis: This hypothesis assumes primary production is more stable and predictable in polycultures than monocultures. This, coupled with spatial heterogeneity of complex agroecosystems, should allow insect species to partition the environment temporally and spatially thus allowing the co-existence of more species.

They conclude saying that further research is needed to clarify whether it is the diversity and productivity of the plant community or the spatial heterogeneity of mixed plantings that gives rise to increased insect species diversity. It seems clear however, that habitat manipulation can aid in pest management by both reducing the pest load and by increasing arthropod diversity, most notably that of predators and parasitoids.

Biocontrol strategies based upon vegetative manipulation that target a pest species must take into account the key natural enemy species and their associated interactions; success or lack thereof is linked not only to the target (pest) but also to other hosts, bioagent habitats and abiotic factors (Stary and Pike, 1999). Ultimately, it is not simply a matter of vegetational diversity but a matter of “functional” diversity determined through investigation and experience (Southwood and Way, 1970). Numerous studies illustrate and document the potential application of plant composition
manipulation and habitat design to enhance biological control of arthropod pests in tree fruit and the particular function related to specific crops and cropping circumstance (Brown et al., 1997; Bugg and Waddington, 1994; Norris, 1986; Rieux et al., 1999; Stephens et. al., 1998; Tedders and Schaefer, 1994).

Early studies demonstrated the potential for habitat manipulation to enhance biological control. Much of that work was done in Eastern Europe (former U.S.S.R.) and in Canada (Leius, 1967). Effects of habitat and cover crop manipulations on arthropod populations in agroecosystems for biological arthropod pest management have been studied in annual cropping systems including truck crops (Bottenberg et al., 1999; Bugg, 1992; van Emden, 1967) and row crops (Ali and Reagan, 1985; Corbett et al., 1991; Fye and Carranza, 1972), perennial systems including citrus (Liang and Huang, 1994), pecan (Bugg and Dutcher, 1993; Bugg et al., 1991; Rice et al., 1998; Smith et al., 1994), grapes (Altieri and Schmidt, 1985; Daane and Costello, 1998) and tree fruit (Alston, 1994; Brown and Schmitt, 1996; Brown et al., 1997; Coli, et al., 1994; Cossentine et al., 1996; Fye, 1983; Haley and Hogue, 1990; McClure et al., 1982; Niemczyk et al., 1996; Nyrop et al., 1994; Stanyard et al., 1997; Wyss, 1995). Reviews citing and case study discussions of numerous habitat manipulation/arthropod pest management examples have been made (Altieri, 1994; Altieri and Letourneau, 1982; Andow, 1991; Bugg and Pickett, 1998; Corbett, 1998; Muma, 1961; Russell, 1989).

One of the earliest such North American studies was conducted in Virginia peach orchards by Bobb (1939). He found biological control of oriental fruit moth increased in the presence of ragweed (Ambrosia sp.), smart weed (Polygonum sp.), lambsquarter (Chenopodium album L.) and goldenrod (Solidago sp.). These plants provided alternate hosts for the parasite Macrocentrus ancylivorous (Hymenoptera: Braconidae). Another early study in Ontario orchards, was conducted by Leius (1967). He found that wild flowers in and about the orchard,
serving as food sources for adult parasitoids, influenced the extent to which host tent caterpillars were parasitized. Orchards with rich flowering undergrowth had much higher parasitism rates. Leius concluded that there was a “a definite relationship between the abundance and variety of wild flowers, on the one hand, and the incidence of parasitism by Hymenoptera, on the other”.

Fye (1983) found pear, *Pyrus communis*, cover crops in Washington to harbor a large complex of general predators. When he planted cereal grains and crucifers as cover crops the major psylla predators were successfully (albeit sporadically) retained. He attributed this to a population of alternate prey being supported by the grains. Extent and type of agroecosystem vegetation can also affect the presence and severity of arthropod pest species and thus be manipulated to mitigate their impact. For example McClure et al. (1982) evaluated peach orchard cover crops. They found that the numbers and species of leafhoppers depended upon which of four orchard ground covers was beneath the peach trees. Brown et al. (1997) and Brown and Schmitt (1996) reported increased diversity of phytophagous insects and greater diversity and populations of hymenopterous parasitoids in young IPM apple orchards planted to a mix of rye, *Secale cereale* and clover, *Trifolium pratense* compared to conventionally managed orchards. They said that the diversified understory flora in IPM orchards provided more habitat for parasitoids and the diverse phytophagous insect populations in those same orchards provided a stable food source for predators. Altieri and Schmidt (1985) evaluated the effects of ground covers in California apple orchards and vineyards compared to clean cultivation. They found that orchards and vineyards with covers generally exhibited 1) less colonization and subsequent infestation levels of aphids, leafhoppers codling moth and other herbivores, 2) more species and more individuals of soil dwelling predaceous arthropods and 3) higher removal rates of artificially placed prey. They found a variety of generalist predators and parasitic Hymenoptera (mainly Braconidae and Ichneumonidae) in cover cropped plantings. Depending on the specific orchard system, cover crop complex and associated arthropod species, they said, manipulation of the ground cover can
have a significant impact on the number of arthropods that inhabit the ecosystem by directly affecting herbivore species that discriminate between trees with and without a cover beneath and by attracting and retaining natural enemies through the provision of alternate prey and other sources of sustenance. They also observed that legume covers that remained in full bloom throughout the season sustained the highest populations of arthropods and as the foliage of various covers senesced and deteriorated nutritionally (supporting fewer phytophagous insects) the complex of predators and parasites narrowed in abundance and species composition. They suggested that the potential of a cover as a reservoir for natural enemies seemed to be determined by the species of cover crop and its structural and phenological characteristics.

Several investigators have evaluated the effects of orchard floor plant composition manipulation to enhance aphid biological control (Bugg and Dutcher, 1993; Haley and Hogue, 1990). Wyss (1994) planted selected flowering plants (weeds) in orchard drive rows and along borders to attract apple aphid antagonists. When the plants were flowering he observed more aphidophagous predators in the weed-planted plots than control plots and aphids were significantly less abundant in weed-planted plots. The most abundant aphidophagous predators in the treated rows were spiders, predaceous Heteroptera, Coccinillidae, and Chrysopidae. Smith et al. (1994) evaluated leguminous covers in pecan (Carya illinoinensis [Wagenheim] K. Koch) orchards. Hairy vetch provided superior habitat for aphids and their predators. The aphids on the vetch extended the availability of food for predators allowing predator populations to build. Upon vetch senescence the predators moved to pecan trees to contribute to arboreal aphid control. Rice et al. (1998) also evaluated ground covers in pecan orchards and found early season aphid populations were frequently lower with a legume cover than with a grass cover. Liang and Huang (1994) report the successful biological control of the red citrus mite (Panachynus citri), via habitat manipulation in 135,000 hectares of citrus in China by the
conservation of the wild flowering plant *Ageratum conyzoides* (and others) on the orchard floor as habitat for natural enemies including red citrus mite predators, *Amblyseius* spp. Alston (1994) determined that the dispersal of phytophagous mites in Utah apple orchards was enhanced by the presence of seven common broadleaf weeds and apple suckers all of which she said served as reproductive hosts for the mites. She correlated total ground vegetation cover (comprised of the seven weed species) with phytophagous and predatory mite populations. She found that orchards with a total ground cover vegetation of 50% or more but with less than 12% cover of reproductive host plants for mites, had predaceous mite populations sufficient to maintain phytophagous mite populations below economically damaging levels.

Collectively these studies serve to illustrate the complexities associated with habitat manipulations in an agroecosystem to enhance biological control. It is not a simple matter of providing a diversity of flora in the agroecosystem. Particular plant species, combinations, ratios, phenology, cover structure and management may be important in a given system. And what proves advantageous or efficacious in one orchard, area or region may not be so in others.

Prokopy (1994) said “managing the seasonal phenology of orchard ground cover in a way that will encourage the establishment and build-up of natural enemies, is not harmful to tree vigor, fruit production and fruit quality, and does not encourage build-up of pests represents a true challenge”. He indicated that manipulating orchard habitat components in a systems approach, for the long-term benefit of pest management, ought to be emphasized by researchers, extension personnel and orchardists. He also said “orchardists should do all that is economically viable to manipulate orchard groundcover and surrounding vegetation toward enhancing opportunity for biological control of orchard pests by natural enemies”. Regarding agroecosystem diversification Sheehan (1986) said answers are needed to many questions including:
1. How important is enemy-caused mortality relative to herbivore movement in influencing pest population response to agricultural system diversification?

2. Does the ecology of herbivore-enemy interactions differ fundamentally between agroecosystems and those less disturbed?

3. Can results of small plot experiments be extrapolated to large-scale agriculture?

4. Can useful generalizations be made about natural enemy response to agroecosystem diversification or must each case/agroecosystem be considered on an individual basis?

Sheehan concluded by saying observations and experimentation will help elucidate ways in which agricultural systems can be manipulated to enhance natural enemy activity but “clearly more extensive and careful experimentation is needed to detect the effects of agroecosystem diversification on both pest abundance and on control by natural enemies”. Gross (1987) in discussing entomophagous insect augmentation and enhancement and Bugg (1992) in his discussion of cover crop usage to manage arthropod pest of vegetable crops both concurred. In support of the same notion Flint and Roberts (1988) conveyed the sentiment that the strategy of using plant diversity to manage insect pest problems has potential value for large and small farms alike particularly when viewed over time and on a area-wide basis.

**Leafroller parasitoids**

Leafrollers have many natural enemies including general predators as well as several species of parasitic wasps and a parasitic fly (Beers et al., 1993; Ohlendorf, 1999). The potential for leafroller biological control by parasitoids is thought to be substantial in orchards using mating disruption and in which the use of broad-spectrum pesticides is greatly curtailed or eliminated.
Li et al. (1999) cite that 14 hymenopteran and two dipteran parasites were recovered from leafrollers collected in unmanaged Ontario apple orchards and over 20 parasitic species have been found in C. rosaceana in the apple growing Okanagan and Similkameen valley districts of British Columbia.

The most effective beneficials in agriculture are usually species that are perennially present in the farmlands (Stary and Pike, 1999). In Washington’s apple orchards several species of parasitic wasps (order Hymenoptera) and a parasitic fly (order Diptera) are known to attack obliquebanded, P. pyrusana and other fruit tree leafrollers.

The Tachinidae (Diptera) is the most important of the 12 or more families of parasitic flies (Flint and Dreistadt, 1998). Tachinidae is a very large family of parasitic insects with more than 1,000 species in North America, many of which are important natural enemies of phytophagous lepidopteran pests. Their impact on agricultural pests and fruit tree leafrollers is not well documented or understood. Most tachinids have a wider range of hosts than do parasitic Hymenoptera and all are endoparasitoids. Tachinid flies attack larvae of leaf rollers (and other insects including beetles, sawflies and stinkbugs). Five different genera of tachinids have been reared from fruit tree leafroller larvae (Beers et al, 1993; Pedigo, 2002).

Tachinids are typical fly (housefly) -like insects, however size and appearance varies with the species. Generally they are robust and dark grey or black, hairy and can be distinguished by thick bristles on the tips of their abdomens. Unlike other parasitic flies, the tachinids have specialized abdominal structures for ovipositing on or in their hosts. Often their large, white, oval and flat eggs can be seen on the head and thorax regions of larvae that have been attacked. Larvae (maggots) of tachinids develop within host bodies. Tachinid pupae are dark, reddish
brown and oval. Adult tachinid flies can be observed visiting flowers in and near orchards.
(Beers et al, 1993; Flint and Dreistadt, 1998; Pedigo, 2002).

Tachinids are regarded as effective biological control agents because of their ability to build up large populations quickly. They exhibit many life cycle variations. Some have only one generation per year and spend much of their lives as pupae while others complete a life cycle in only a few weeks and have multiple generations per year. The life cycles of some tachinids seem to correspond well with that of their hosts so if the host overwinters as a larva the tachinid also overwinters as a larva within the host. Some tachinids overwinter as pupae in the soil or duff. Adult tachinids emerge in the spring and feed on flower nectar and insect honeydew, mate and females then begin their search for hosts. Host larvae are generally attacked in the mid- to late larval instars. Tachinids exhibit varied oviposition strategies (Beers et al, 1993; Mills and Carl, 1991). Regardless all young tachinid larva feed their way into their host where they consume the gut wall. Most nearly completely consume their host larva before boring out to pupate. Tachinid pupae are generally found close to former host remains. Some tachinids do not kill their hosts until after the host pupates. (Beers et al, 1993; Flint and Dreistadt, 1998; Mills and Carl, 1991; Pedigo, 2002). Flint and Dreistadt (1998) note that the tachinid Erynnia (= Anachaetopsis) tortricis is an important parasitoid of moths in the family Tortricidae including the obliquebanded leafroller. This endoparasite lays one to several eggs on the head or thorax of a host larva. Their hosts do not die until after they pupate. In addition to E. tortricis Mills, Carl (1991) lists 18 additional major Nearctic and Paleartctic tachinid parasitoids of tortricid pests of orchard crops.

Seemingly very little information exists regarding Tachinid parasitism of apple leafrollers. James (1976) reports rearing Erynnia tortricis from the fruit tree leafroller Archips argyrospilus (Walker) in Washington State. Regarding apple leafroller biological control Brunner (1997b)
reported that a "parasitic fly in the family Tachinidae is often the most common parasite in
unsprayed or non-bearing blocks, especially in northeast Oregon and the Columbia Basin".

Mayer and Beirne (1974b) reared five parasitic tachinid species from seven leafroller species
feeding on apple in the Okanagan Valley of British Columbia. They were tachinids: *Nemorilla
pyste* (Walker), *Hemisturmia tortricis* (Coquillet), *Pseudoperichaeta erecta* (Coquillet),
*Comsilura concinata* (Mg.) and *Eumea ceasar* (Ald.). In field studies with *P. pyrusana* and
obliquebanded leafrollers in Yakima, Washington apple orchards, Knight et al. (1998) observed
rates of 40-80% parasitism by the tachinid species *N. pyste* (Walker) and *P. erecta* (Coquillet).

Knight (2001) also surveyed *P. pyrusana* infestations in Yakima, Washington area apple (*Malus
domestica*, Borkh), cherry, (*Prunus avium* L.) peach/nectarine (*Prunus persica* (L.)), pear (*Pyrus
communis* L.), apricot (*Prunus armeniaca* L.) and prune (*Prunus domestica* L.) orchards. He
found tachinid parasitism for all leafrollers collected to be 37% for the overwintering generation
and 27% for the summer generation. Phillips (1983) reported parasitism of the common earwig,
*Forficula auricularia* by tachinid flies in English apple orchards. Horgan et al. (1999) monitored
the introduced tachinid parasitoid *Cyzenis albicans* (Fallen) of winter moth, *Operaopherta
brumata* on blueberry in British Columbia. They determined that the parasitoid caused
significant mortality of the winter moth. Chao (1984) reported there are about 500 species of
tachinid flies in China but only 25% of them are identified with their hosts. He and his
colleagues have found as many as 23 different tachinids parasitizing one host species. He
considers tachinid flies to be "potent" biological pest control agents but recognizes only a few of
them are capable of suppressing pest populations to significant degrees. Chao (1984)
recommended "guaranteeing the availability of nectar-yielding plants to attract and feed tachinid
species". He further states that choice of plants for this purpose "must be carefully arranged
according to the different groups of tachinid flies with different feeding preferences". Altieri et
al. (1993) discuss surveys conducted in relatively unmanaged apple orchards that revealed a high
species richness of parasitic Hymenoptera. In Wisconsin 178 species of parasitic Hymenoptera were detected and in Indiana 102 species. The dominant families were Eulophidae, Braconidae, Pteromalidae, Encyrtidae and Ichneumonidae. Dominant genera were *Tetrastichus*, *Sympiensis*, *Pteromalus* and *Apanteles*.

There are more than 1,700 species of braconid wasps in North America. Most are quite small, usually less than 15mm long and their bodies tend to be short and slender. Many species are biological control agents of agricultural crop pests and though hosts vary most braconids prey on Lepidoptera (Beers, 1993; Pedigo, 2002). The most important parasitic wasps attacking apple leafrollers in Washington State are species in the families Braconidae and Eulophidae. Most are endoparasitoids though some, like many parasitizing apple leafrollers are ectoparasitoids (Beers et al., 1993; Pedigo, 2002). Parasitoids in the superfamily Chalcidoidea such the eulophids are generally smaller (about 2 to 3 mm) than braconids. They are often a dark metallic green and have clear wings with few veins. Chalcid wasps attack eggs, larvae or pupae of lepidopteran fruit pest and other insects. There are an estimated 25,000 described species of (and more than 2000 North American species) of chalcid wasps including some eulophid parasites of fruit tree leafrollers. Many chalcid species have been utilized in classical biocontrol attempts (Beers et al., 1993). The following will describe two parasitoids, *Apanteles* spp. and the Eulophid *Colpoclypeus florus*, considered to be the primary braconid parasitoid natural enemies of apple leafrollers in Washington and those having the most potential to exert some degree of biological control.

The braconid genus *Apanteles* (subfamily Microgastrinae) contains over 1150 recognized species (Shervis and Shenefelt, 1976). Over 200 species in North America are parasites of exposed-feeding Lepidoptera. Several species are important larval parasitoids commonly attacking
leafrollers in commercial orchards. These same species likely attack other lepidopteran hosts as well (Beers et. al., 1993; Flint and Dreistadt, 1998).

Just as for the tachinids, Shervis and Shenefelt (1976) note that little information regarding braconids (including Apanteles sp.) exists. Leafroller parasitism by Apanteles sp. in apple is no exception. Mayer and Beirne (1974b) reared Apanteles cacaoeciae (Riley) and another unidentified Apanteles sp., in addition to six other braconids from four of seven leafroller species feeding on apple in the Okanagan Valley of British Columbia. They considered A. cacaoeciae to have significant potential as a leafroller biocontrol agent. Evenhuis and Vlug (1973 discussed two particular Apanteles species they found parasitizing apple leafrollers in the Netherlands. While studying Apanteles species reared from apple leafrollers they reported often rearing two closely related species, A. atar (Ratzenburg) and A. xanthostigma (Haliday). They described A. atar as a gregarious specialized parasite of leafrollers and A. xanthostigma as a solitary one with a lesser known host range though they speculated that it may prefer leafrollers as hosts. Additionally they reported that the former species preferred larger larval instars than did the later. In a subsequent report Evenhuis and Vlug (1983) said they reared seven Apanteles species from apple leafrollers and A. atar and A. xanthostigma predominated. They said A. atar must be considered a specialized parasite of various Tortricidae. Conversely they described A. xanthostigma as a polyphagous parasite of Lepidoptera. Evenhuis and Vlug (1983) reared other Microgastrinae parasitoids from apple leafrollers but in so few numbers that they considered them insignificant contributors to natural control of apple leafrollers. Nine hymenopteran parasitoid species were reared from obliquebanded leafrollers collected in the vicinity of Vancouver, British Columbia by Doganlar and Beime (1978). They found A. atar and A. longicauda (Wesm.) to predominate. Parasitism levels approached 10 percent. Coop et al. (1989) reported leafroller parasitism (including obliquebanded leafroller) by A. aristotelia on
Rubus spp. in Oregon and Washington. Similarly, various other Apanteles species have been reported associated with various crops such as alfalfa (Allen and Smith, 1958) and their phytophagous lepidopteran pests.

Exact species attacking apple leafrollers in Washington apple orchards have not been fully identified but A. atar is thought to be prevalent. Apanteles overwinter inside a leafroller host larva. Apanteles larvae begin to grow, feeding on its host’s organs, as the host leafroller larva matures in the spring. The host is killed. Upon maturity Apanteles larvae leave their host and spin individual cocoons within the rolled leaf retreats of their deceased host. Cocoons of Apanteles can be found in May and early June in Washington orchards, which is about the same time that unparasitized leafroller larvae are beginning to pupate. Host larva remains are usually evident as black, shriveled masses near the parasitoid cocoons. Emergence of adults generally occurs within seven to ten days and when summer generation leafroller eggs hatch, in late June to early July, newly emerged adult Apanteles attack newly hatched host larvae. They appear to prefer larger larval hosts (Evenhuis and Vlug, 1983). Cocoons can again be found in late July to early August (Beers et al., 1993).

The larva of Apanteles is a typical creamy white to light green maggot. It spends most of its time within its host. Pupae are contained within a white fuzzy cocoon that is oblong and about 3-4 mm long. Up to fifteen cocoons will be found within a leafroller retreat. Adult Apanteles are 3-5 mm long with black bodies and long antennae. Females have short ovipositors terminating their abdomens (Beers et al., 1993).

The chalcidoid wasp Colpoclypeus florus Walker (Hymenoptera, Eulophidae) is considered to have significant potential as a biological control agent for apple leafrollers in Washington and in Europe (Brunner, 1996; Gruys and Vaal, 1984; Pfannenstiel, 1997). As such, in Europe, it has
been subject to a great deal of investigation. It is described by VanVeen et al., (1985) and Milonas and Savopoulou-Soutani (2000), as an oligophagous, gregarious, non-paralyzing ectoparasitoid of tortricid leafroller species. In Europe the wasp has been recorded attacking 32 host species (Dijkstra, 1986; Gruys and Vaal, 1984; VanVeen and Van Wijk, 1987). This parasitoid has a western paleoarctic distribution and is rarely found in natural or semi-natural habitat (Dijkstra, 1986). In Europe it is considered to be the most promising parasitic hymenopteran for the control of leafrollers in apple orchards with reduced insecticide input (Evenhuis and Vlug, 1983). Soenarjo (1979) reported 40 - 90% summer fruit tortrix parasitism levels by *C. florus* in Dutch orchards. Panizza Dalla Monta and Gambro (1973) reported late season parasitism levels by *C. florus* in Italian orchards to have reached 95%.

*C. florus* eggs (found on host larvae retreat webbing) are slender and slightly curved, less than 1 mm long and creamy white. Larvae are maggot-like, bright to dull green in color, and 1mm to 4mm in length depending upon stage. Pupae (also found within host webbing) are light brown at first but turn black. They are 3 - 4 mm long. Adult female *C. florus* have a black thorax and a light brown to golden abdomen. Two small dark spots are apparent on the ventral base of the ovipositor. Antennae are short. The male wasp is slightly smaller with a black thorax and abdomen and a creamy white area on the ventral abdomen (Beers et al., 1993; Brunner, 1996).

It is assumed that *C. florus* will demonstrate a similar life history in Eastern Washington as in Europe. There the parasitoids overwinter as mature larvae on a consumed host larvae. Pupation occurs in the spring when orchard leafroller larvae are present. Large (fourth - fifth instar) host larvae are stung in the head by a female that then remains with the stung larvae inside the webbed, leaf shelter. The female then lays eggs on the abnormally dense webbing produced by the stung host. Eggs hatch and parasitoid larvae locate host larvae and begin external feeding. The host larvae remains alive until feeding of the final *C. florus* instar begins (Beers et al., 1993).
The number of parasites that can develop successfully on one host depends upon larval size (Evenhuis, 1974; VanVeen et al., 1985). VanVeen et al. (1985) reported the ability of females (virgin and inseminated) to regulate their clutch size according to larval host size. The number of hosts parasitized by an individual in the field is about 2-3 per female. This low level of parasitism is perhaps in part accounted for by the extremely long time (up to 56 hours in the field) taken to parasitize a single host (Dijkstra, 1986). There appears to be only two generations of *C. florus* per year in Washington as opposed to 4-8 generations reported in Europe (Beers et al., 1993; Gruys and Vaal, 1984).

Though *C. florus* is considered the primary parasite of leafrollers in European orchards and to have the greatest potential to afford leafroller biocontrol in integrated pest management programs, the parasite is found only sporadically in orchards during the early spring and fall. Parasitism from the wasp in the summer though, can be high (Gruys and Vaal, 1984). The life cycle of *C. florus*, it seems, is not well synchronized with most orchard leafroller species and few latter generation wasps find suitable larval hosts of an advanced (fourth-fifth instar) stage of development. Consequently *C. florus* appears to leave the orchard to overwinter on suitable hosts elsewhere. This results, it is believed, in the scant spring presence and fall/winter absence of *C. florus* in apple orchards (Brunner, 1996; Evenhuis and Vlug, 1983; Gruys and Vaal, 1984). Evenhuis (1974) stated that where *C. florus* resides in the spring and early summer is a puzzle. Likewise where and with what host *C. florus* overwinters is also unknown (VanVeen et al., 1985).

*C. florus* was first reported in Washington by Brunner (1994, 1996). His report constituted an extension of the specie’s known geographic distribution. *P. pyrusana* leafroller, likewise, was a new host record. *C. florus* was introduced to North America from a release of French specimens to control *A. velutiana* in Ontario, Canada. Recovery of *C. florus* from obliquebanded leafroller
and *S. ocelluna* in Southern Ontario was reported by Hagley and Barber (1991). It is thought that *C. florus* subsequently became established in British Columbia by the mid-1970’s (Brunner, 1996).

Brunner (1996), in his investigations of the occurrence of *C. florus* in north central Washington, observed low orchard leafroller parasitism levels (0 - 13%) during the spring in all test orchards, and no *C. florus* was found. Summer leafroller parasitism levels were higher, particularly in unsprayed orchards. *C. florus* was deemed responsible for approximately 75% of observed leafroller parasitism. *C. florus* was also observed in other north central Washington orchards suggesting a wide-spread regional distribution.

There are several orchards in north central Washington in which *C. florus* is reported established and providing 50 - 60% spring leafroller parasitism and 70 - 80% parasitism in the summer (Brunner, 1996). Up to 98% parasitism by *C. florus* in unsprayed apple orchards in Washington in reported by Brunner (1997b). Brunner (1996) states that *C. florus* in Washington may constitute another natural enemy to combat orchard leafrollers and that the high levels of parasitism noted in unsprayed orchards indicates that *C. florus* is well adapted to the eastern Washington climate in the absence of broad-spectrum insecticides. In a subsequent study Brunner et al. (2001) reported that organophosphate and carbamate pesticides were extremely toxic to *C. florus*, and diflubenzuron caused severe sublethal effects, completely blocking reproduction. Other pesticides including pyrethroids, imadacloprid and abamectin also proved toxic. They also found that biorational pesticides such as soap, oil and *B. thuringinesis* caused no toxicity to *C. florus*.

A frequent and main limitation to effective biological control by parasitoids in agroecosystems is the lack of hosts for host alternation and relationships (Stary and Pike, 1999). In this context the
utility of *C. florus* as a consistent biological control agent has one distinct limitation. As in Europe, Washington orchard leafroller species are not appropriate overwintering hosts for *C. florus* which requires large (fourth - fifth instar) larvae (Brunner, 1996). Obliquebanded leafrollers and *P. pyrusana* overwinter as smaller (second - third instar) larvae (Beers et al., 1993). *C. florus* therefore may not occur (because of low endemic overwintering populations) in Washington orchards in sufficient numbers to economically control *P. pyrusana* and oblique banded leafrollers in the spring (Brunner, 1996). Future success with *C. florus* as a leafroller biocontrol agent may depend upon the identification and utilization of an appropriate overwintering host (Alway, 1997a; Pfannenstiel, 1997).

**An alternate host for Colpoclypeous florus**

The native Washington tortricid moth, *Xenotemna pallorana* is a leafroller that has been identified, initially evaluated, and considered a potential alternate (overwintering) host for *C. florus* in Washington orchards (Nobbs, 1997). This widespread North American species feeds primarily upon native legumes, cultivated alfalfa and white clover (Chapman and Lienk, 1971). It has been reported as a pest of rose (Schott, 1925), young (white, red, Scotch and Jack) pine (McDaniel, 1936), strawberry (Smith, 1941), birdsfoot trefoil (Neunzig and Gyrisco, 1955), and alfalfa (Snow and McClellan, 1951). Newcomer and Carlson (1952) reported *X. pallorana* as being very common in the Yakima valley of eastern Washington. They said it could be found in fruit orchards but more often on shrubby and succulent plants including alfalfa, sweet clover, dock, goldenrod, lambsquarter, milkweed, mullein, sumac, sycamore, willow, Canada thistle, and asparagus. They went on to say that it had not been a serious pest of fruit with the exception of occasional partial defoliation of young apple trees. They described *X. pallorana* eggs as being laid in clusters on leaves, yellowish in color and not overlapping. Snow and McClellan (1951) described *X. pallorana* eggs somewhat differently saying they are pale green, shingled masses
which take on an orange color before hatching and are laid on upper leaf surfaces usually within several inches of shoot apices. Newcomer and Carlson (1952) described larvae as typically (for leafrollers) active and wriggly when disturbed. They described the larvae as lighter and greener colored than *P. pyrusana* larvae, with a rather pointed last abdominal segment (as viewed from above) and a green head capsule. Additionally they described *X. pallorana* pupae as blackish in color with lighter areas on the abdomen and adults as cream colored or light tan without distinguishing markings.

Snow and McClellan (1951) made observations of the natural history of *X. pallorana* on alfalfa. They noted that larvae passed the winter partially grown and were on the first spring growth where they folded single or several leaves together with webbing. Larvae of various instars were detected in late May through early June. Overwinter generation adults were first observed in mid-June and large numbers were trapped from the end of June through the latter days of July. Egg masses were first found in late June and fresh masses were readily found through the first 10 days of July. Larvae upon hatching from an egg mass dispersed rapidly some crawling to other leaves and foliage and some dropping to the ground from a thread (Snow and McClellan, 1951). Initial feeding was confined to upper leaf epidermis but full grown larvae formed webbed feeding retreats. Snow and McClellan (1951) also noted that larvae formed webbed retreats in the shape of a tube out of host plant racemes and that some larvae had more than one retreat of this kind. Pupation took place primarily in August within the protection of webbed leaves or racemes. Second generation moths were observed from mid-August to the end of September. Summer generation eggs were found at the end of August and newly-hatched larvae in mid-September. Immature larvae were found in early October on fall host plant growth.

According to Chapman and Lienk (1971) tree fruit crops are likely secondary hosts of *X. pallorana* used to complete its life cycle when preferred hosts (legumes) are unavailable. When
*X. pallorana* does infest fruit trees it is usually restricted to the lowest portions of the tree canopy growing closest to cover crop plants in which eggs are preferentially laid. They also indicated that the life cycle of *X. pallorana* is very similar to those of the obliquebanded and pandemis leafrollers but that it overwinters in an advanced (fourth - fifth instar) larval stage.

Nobbs (1997) determined that *C. florus* females will oviposit on host in the orchard ground covers but preferentially choose hosts on fruit trees and that *C. florus* will find and parasitize *X. pallorana* on cover crops and obliquebanded leafroller in apple trees. Brunner feels that because the native Washington leafroller *Xenotemna pallorana* will not preferentially feed on fruit trees and has a similar life cycle as fruit tree leafrollers but overwinters as a mature larvae it could prove to be a suitable overwintering host for the leafroller parasitoid *C. florus* (Nobbs, 1997).

**Cover crop influence on fruit tree growth and orchard management**

Apple trees are generally considered poor competitors with understory plant species. Cover crops and orchard floor management practices directly affect tree performance (Woolridge and Botha, 1991). The effect of competition is expressed in terms of fruit production, tree growth or fruit quality (Forshey, 1988; Marsh et al., 1996; Marsh et al., 1998). Vegetation on orchard floors varies greatly between orchards and growing regions. The nature of an orchard floor plant community and its management can have a profound influence on orchard performance and ease of operation (Elmore et al., 1989, Connell et al., 2001). In addition to potentially providing habitat for arthropod population diversification and enhancement, cover crop use in orchards has several benefits including mitigation of water run off and soil erosion, increased water penetration, addition of organic matter, recycling of nitrogen, increased pH, hindrance of harmful weed establishment, ease of operations and dust reduction. However, ground covers also compete with orchard trees for water, nutrients and possibly oxygen, reduce lateral rooting and
degree of mychorrization as well as other soil biotic activity, may offer flowers visited
preferentially by insect pollinators to the detriment of fruit tree pollination (Forshey, 1988;
Marsh et al., 1996; Nielson and Hogue, 1985; Skroch and Shribbs, 1986; Woolbridge and Harris,
1989) and may harbor detrimental vertebrate and invertebrate pests (Byers, 1984; Jaworska,
1996; Meagher and Meyer, 1990; Merwin et al., 1999). Ground covers affect abiotic orchard
factors such as ambient and soil temperatures, soil texture and compaction (Meagher and Meyer,
1990; Nielson et al. 1986). As such ground cover management in orchards has long been a
subject of horticultural investigation as evidenced by the work of Bedford and Peckering (1914),
Howard (1924), Blackmon and Barnette (1936), Neilson and Hogue (1985) and Marsh et al.
(1996).

Nielson et al. (1984) compared sod and clean cultivated orchard floor management systems on
‘Golden Delicious’ nitrogen nutrition and tree growth. They found significant reductions in leaf
nitrogen levels and trunk growth in trees with the sod orchard floor. Fruit was also smaller but
firmer and more highly colored from trees in the sod floor plots due to nitrogen depletion by the
sod. They concluded that nitrogen nutrition was highly responsive to orchard floor management.

Competition from orchard floor plants is a particular concern for newly established and young
apple trees (Woolbridge and Harris, 1989). Nielson and Hogue (1985) compared four soil
management treatment effects on young dwarf ‘Red Delicious’ apple trees. One treatment was
full sod cover and the other three were some sort of understory vegetation reduction. Leaf
nitrogen concentration was reduced in sod cover treatment trees and total weight of fruit
harvested was smaller. They also observed a sod induced potassium: magnesium antagonism.

They said ground cover management strongly influenced early growth of the young apple trees
in their experiment. Shribbs and Skroch (1986) evaluated 12 ground cover systems on young
‘Smoother Golden Delicious’. They found that cover significantly influenced relative growth
rates of trees, stem diameter, shoot length, leaf length and yield. Mulched, bare ground and cultivated treatments had greater tree growth than cover crop treatments. The two leguminous covers had greater tree growth than the grass and non-leguminous broadleaf covers. Woolridge and Harris (1989) likewise determined that various cover crops negatively impacted young fruit tree growth compared to a clean, weed-free orchard floor maintained with herbicides. Meyer et al. (1992) demonstrated that peach tree growth rate and survival was dramatically impacted by the kinds of plants composing the orchard floor and that tree survival was greatest and growth optimized with bare ground. Meagher and Meyer (1990) also evaluated different ground cover strategies in peach orchards. Consistent with other reports, bare ground plots resulted in greater tree growth and yield than did alternatively-managed, weedy plots. Leguminous, grass and mixed herbaceous apple orchard understory covers were evaluated by Marsh et al. (1996) in New Zealand. They found tree nitrogen levels to be higher in legume-covered orchards. Fruit maturity was delayed, fruit nitrogen levels increased and fruit soluble solids and firmness levels decreased in those blocks. No increase in incidence of storage disorders was detected however. They said that these changes in fruit quality and maturity highlighted the importance leguminous understories as contributors to tree nutrition.

Others have evaluated and noted the influence of orchard covers on orchard critical abiotic factors. Nielson et al. (1986) compared sod-covered management with other apple orchard understory management strategies including total vegetation control with herbicides, shallow tillage and black plastic mulch. The full sod ground cover treatment resulted in the coldest soil during the growing season but the warmest during the winter and had the lowest yield. Similarly Meagher and Meyer (1990) also found bare ground orchard plots to have higher soil temperatures than those with sod or strip-sod covered understories. Additionally, plant-covered understories exhibit reduced soil moistures compared to bare understories (Meagher and Meyer,
Skroch and Scribbs (1986) found that leguminous orchard covers reduce soil moisture availability more than grass covers do. Hogue and Nielson (1987) and Skroch and Scribbs (1986) reviewed effects of orchard floor vegetation management on fruit tree growth and development and on abiotic factors in orchards.

Some investigators report increased incidence of insect pest damage associated with various orchard cover crops (Meagher and Meyer, 1990; Meyer et al. 1992; Skroch and Shribbs, 1986) but a major pest concern relative to orchard ground covers is field mice (*Microtus* sp.) which feed upon tree roots and trunks during the winter Byers (1984). Merwin et al. (1999) evaluated the influence of several apple orchard cover crops on winter tree damage by mice. They found the highest vole populations and levels of damage to occur in the leguminous, crown vetch-covered plots. Cover crop shoot and leaf biomass production was a significant predictor of mice populations. Byers (1984) however, in his discussion of orchard cover crops for vole biological control, indicted that several genetic lines of alfalfa have been shown to result in poor weight gain of mice due to poor acceptance as a food and/or the presence of antimetabolites. As such alfalfa may be a preferred leguminous orchard cover species. Jaworska (1996) cautions though that if herbaceous plants are cultivated as apple orchard covers to enhance arthropod biological control it will be necessary to pay more attention to the management of rodents.
CHAPTER TWO

GENERAL MATERIALS AND METHODS

Plot Establishment

The experiments described herein were conducted from the spring of 1999 through the winter of 2002 and were inclusive of four growing seasons. Experimental plots were established in a 3.12 hectare, 5th leaf, mature-bearing Fuji (BC 2/M9) apple block at the 145 hectare Wenatchee Valley College- Grady and Lillie Auvil Teaching and Demonstration Orchard in East Wenatchee, Washington. Elevation of the orchard was approximately 366m above sea level. The laboratory orchard is located in a major and expansive deciduous tree fruit growing district and is in proximity to many apple, cherry and pear orchards. Additionally, a packing shed with its attending stacks of tens of thousands of apple bins brought out from cold storage throughout the growing season, was located to the northwest approximately 1000 meters away. Winds blowing across the orchard, that might be a factor in insect immigration, were predominately southeasterlies. Average precipitation for this region is 20.3 to 25.4cm per year. Average winter temperature is 0 ° C with an average daily minimum temperature of -4 ° C. Summer average temperatures are approximately 22 ° C with an average daily maximum temperature of about 28 ° C. Soils in the block were representative of the area. They are classified as a fine sandy loam with some relatively coarse material. Top horizons are typically 15cm to 60cm deep (Beieler, 1981).

The trees in the block were planted at a spacing of 1.2m X 3.96m for an approximate density of 1,977 trees per hectare. They were trained to a modified HYTEC system typified by a central axis conical shape and aggressive lateral renewal (Barritt, 1992). They were supported on an upright, 3-wire, 3m high, trellis. Tree rows ran nearly north-south. The northern boundaries of
the block abutted wild habitat that was sparsely covered with low growing grasses and shrubs typical of the semi-arid central Washington region. This extended for 100m or more until coming to the blacktop of a commercial airport runway. The eastern borders of the experimental block were adjacent to contiguous apple orchards planted 3m away. Much of the southern border was approximately 25m from a sweet cherry/English walnut orchard with the typically sparse, low growing, wild vegetation growing in the region separating the two orchards. Other portions of the southern boundaries abutted to a greater expanse of wild vegetation and pasture. On the west the block was mostly adjacent to a sweet cherry orchard. On the northern 2/3rds of western border the cherry trees were only 3 m away. The southern 1/3rd of the western border was separated from the cherry orchard by a 30m wide ravine covered with wild vegetation.

The 3.12 hectare block was divided into six contiguous plots varying in area from 0.49 to 0.57 hectares and containing from 1004 to 1056 trees each. Plots were configured to minimize borders with adjacent plots and to maximize distance between a designated, core sampling area situated in the interior of each plot. At least 31.6m separated each plot’s core sampling area from adjacent plot core sampling areas within the block. The core sampling area for each plot, configured to be central to an individual plot, was approximately 0.12 ha in size. Additionally, a ‘star’ configuration of sample trees (numbered 1-30) was delineated for each plot. The ‘star’ consisted of a transect row of trees extending from the north- south boundaries of each plots core sampling area to the plot center with four arms originating at the plot center and radiating tangentially and equally from the transect row. A randomized block design was used (Davis, 2000; Snedecor and Cochran, 1976). The two treatments of alfalfa or grass covers were equally and randomly assigned to each of the six approximately 0.5 hectare plots with three replications of the grass cover treatment, plots G1, G2, and G3, and three replications of the alfalfa cover treatment, plots A1, A2, and A3 (see Appendix A). A dirt road separated plots A3 and G3 in the
south from the more northerly A1, G1, A2 and G2 plots. Thus there were three replicate blocks; each containing two experimental cover treatments plots.

Tree growth within the block was relatively uniform though some weaker areas (with coarser, more shallow soils) were evident. During the winter of 1999 trees in the experimental block suffered severe “southwest injury” (Childers et al., 1995) that separated bark from the trunk and extensively damaged the vascular cambium and conductive tissue of affected trees. Approximately 75% of the trees suffered some level of damage and about 25% of the trees had to be replanted the following spring in year two (2000) of the experiment. Some remaining trees exhibited reduced vigor and yield. Many recovered fully. Some plots in the block suffered more extensive tree injury and had greater rates of replant. The two southernmost blocks (A3 and G3) suffered the least damage.

Both alfalfa and grass plots were sown with their respective cover cultivar in the spring (May, 21) of 1999, the initial year of the experiment. A standard grass orchard cover mix of perennial rye and red fescue was utilized for the grass cover treatment while ‘Vernal’, an older, drought tolerant, lower vigor cultivar, was utilized for the alfalfa cover treatment. Both were commercially available from Cenex-AG Supply Company (Wenatchee, WA). The grass mixture is trade-named ‘Partner Grass’. The plots were covered with endemic weed species prior to cover establishment and a 1.52m wide, tree row, weed free strip was maintained with glyphosate herbicide per standard orchard management practice. The weed strip was maintained throughout the experiments duration. The soil was prepared for sowing by shallow (2.5-5cm) cultivation with a PTO driven tiller. Sowing was done using a Brillion seeder. Seeding rates were 49.5 kg per hectare for both alfalfa and grass covers. The alfalfa seed was inoculated with *Rhzobium sp*. Initial stands of both covers were consistently insufficient and in 2001 (year three of the experiment) all plots were over-seeded to improve the cover stand. Additionally at this same
time the grass cover plots were treated with the herbicide 2,4-D to reduce broadleaf weed infestation.

**Plot Management/Horticulture**

The orchard block was farmed utilizing standard practices with the exception of arthropod pest management. All plots were uniformly cultivated. Mating disruption was used for codling moth (*Cydia pomenella*) management. Isomate-C (Pacific Biocontrol, Vancouver, WA) pheromone emitters were dispensed in the treatment plots per standard recommendations and practice (1000 emitters per hectare, placed high in the canopy and evenly dispersed on relatively even terrain). It should be noted that lower emitter rates (500 per hectare) were administered. The block had successfully been under codling moth mating disruption since its establishment. Other than a single, delayed dormant (Childers et al., 1995), superior oil application (at 11.3 liters/378 liters of water) no insecticide treatments or other insect control tactics were utilized in the plots for arthropod management during growing seasons. An exception was the removal of codling moth infested fruits in 2002. In years one and two of the experiment post-bloom fruitlet thinning was accomplished, per standard recommendations and practice, with tank mixes of the plant growth regulator/insecticidal material carbaryl (Sevin XLR Plus) tank mixed with one or more of the following the plant growth regulating materials; NAA- 200, Amid-thin and Ethrel. The fungicide fenarimol (Dow Agrisciences, Indianapolis, IN) and an adjuvant was also mixed with the early season, post-bloom, fruitlet-thinning treatments. The carbaryl fruitlet thinner was applied at recommended concentrations of 300 to 600 ppm (0.47 to 0.95 liter per 378 liters) and a rate of 153 or 306 liters per hectare. Application timing was at 80% petal fall for the first carbaryl thinning treatments and for subsequent treatments when fruitlets were 10-15 mm in diameter at approximately 1-2 weeks after full bloom. None of these materials with the distinct exception of carbaryl are known to have insecticidal properties. In year three the foliar feed ammonium
Thiosulfate resulted in blossom thinning action and no additional chemical thinning treatments were used. In year four lime-sulfur and fish oil was twice applied as a blossom thinner and then followed with the post-bloom thinners Amid-thin and Ethrel. Other fungicidal and nutrient feed materials were also applied in the delayed dormant and fruit set periods. See Appendix B for a complete record of agri-chemical applications to the plots.

Irrigation was applied throughout the growing season via permanent, low volume, micro emitters ("Maxi-jet" brand) suspended off the ground from the trellis but under the tree canopy.

Annually, approximately 89 cm of water was applied during the growing season as dictated by estimated evapo-transpiration and tree need. Irrigation water dispersal was not uniform and often missed portions of row middles, which contributed to spotty cover establishment. Pruning, in the dormant and summer seasons, was conducted according to standard horticultural practice for high-density central axis trees in which intensive canopy management and large lateral limb removal and renewal is routine (Barritt, 1992). Annual summer applications of glyphosate herbicide were utilized for under-tree weed strip management. A 1.5 m wide, tree row, "weed free" strip was maintained so that the drive row cover between tree rows was approximately 2.4 m wide.

Ammonium nitrate fertilizer (34-0-0) was band applied to all plots each spring prior to bloom or just after at a rate of 88 kg actual N/hectare. Soluble zinc and boron were both applied by speed sprayer in the delayed dormant oil applications each season. Ammonium thiosulfate and urea were applied to all plot trees in spring 2001 and sulfur was applied in the springs of 1999 and 2001. In 2000 ammonium nitrate was hand applied to replant trees only, at a rate of .016 kg N/tree.
For the initial year of the experiment both alfalfa and grass plots were mowed with a rotary deck mower per standard orchard management practice. To avoid damage to the alfalfa plant crowns a concerted effort was made to avoid mowing the alfalfa as low as grass usually is. In general, mowing was kept to a minimum and done approximately twice per season. Alfalfa rows were alternately mowed with approximately 10 days separating alternate row mowing. The rotary mower shredded and seemingly excessively damaged the stems of the alfalfa plants. There was concern that the damage would have an adverse effect in terms of insect habitat suitability. As such a front mounted sickle mower was manufactured and it was used to mow plots of both treatments and injury to alfalfa plants was greatly reduced.

**Soil Fertility and Plant Nutrition Assessment**

General soil fertility status was assessed for the drive rows and tree rows in each plot by soil sample analysis each November after harvest. Drive row and tree row soil samples were collected, with a sampling tube, at a depth of 30.5cm. For this sample, ten individual, randomly collected core samples were obtained and mixed to make a composite sample submitted for analysis. A commercial laboratory (Cascade Analytical, Wenatchee, WA) analyzed the samples for N, P, K, S, Mg, Ca, Mn, B, Zn, Mo, Cu, Fe, pH and organic matter (OM) content. Additionally, soil N levels in tree rows and drive rows were assessed throughout the growing season by taking samples for analysis in late March (before fertilizer application), early May (after fertilizer application), late summer (latter part of August- early September) and early November. Five soil cores taken from the depth of 0.0 to 30.5cm were randomly collected and made into a composite sample for a tree row or a drive row for each replicate. Spring and late summer (March, May and August/September) analysis was not done in the initial year of the study (done only for years two, three and four); November sample was collected in all four years. Leaf tissue was collected, per standard procedure (10 healthy, mature leaves from moderately
vigorous shoots exposed to full sunlight at chest height per tree and made into a composite sample) from 30 trees in each plot, mid-July each year of the experiment for N, P, K, Ca, Mg, B, Zn, Fe, Cu and Mn content analysis. Tissue analysis was done by a commercial laboratory (Cascade Analytical, Wenatchee WA).

Cover Crop Composition and Nitrogen Content

In mid-July the composition of the cover crop vegetation was evaluated (years two, three and four). Ten sites in each replicate were randomly selected and the number of each prevalent plant species in a 1-meter (indicated by placement of a pre-made hoop) diameter circle were recorded. The nitrogen content of cover crop plants was evaluated by clipping and collecting vegetation at 15 cm above the soil level (our mowing height) from each of three 1-meter sample sites in each replicate. The three randomly selected site samples were combined for each replicate and were sent to a commercial laboratory for N content analysis. In year four N content per unit of biomass was calculated for both cover crop treatments.

Tree Growth

Overall tree growth was measured by identifying ten groups of five trees each in each replicate (total of 50 trees per plot) and measuring circumference of trunks at 20 cm above the graft union. Exact point of measurement was marked on each sample tree in the initial year. Trees were chosen for uniformity and as representative of the block. Measurements were taken from these same trees in early spring (April) of each year before tree growth began. Many originally selected trees suffered winter injury in 1999-2000. Replacement trees were selected in the spring of year two and included in subsequent growth measurements. Additionally, shoot growth measurements were taken at the end of the grand growth period (indicated by terminal bud set). Ten trees were pre-selected per plot and uniformly representative branches were chosen on each
of the ten trees. Shoot length was measured and recorded for three shoot-type classifications; true terminal shoots, true lateral shoots, and bourse shoots.

Yield, Cullage Rates and Cause

Each replicate was harvested to determine yield. Additionally, each year the total cullage rates were estimated and a cull analysis performed. Field sorting was performed as a harvest function; that is damaged apples were discarded on the orchard floor as they were picked and not placed in a bin for transport to the packing shed. Cullage rates were estimated by gathering all culled fruit on the orchard floor for a representative row and extrapolating that to the whole plot. Additional cullage from the packing process was added to field cullage to indicate total cullage rates. Cull analysis was performed by randomly selecting 100 cull apples from each plot. Cause of cullage was determined by visual inspection of each collected fruit. All causes of cullage for each apple were identified and recorded; as such any given apple may have exhibited multiple reasons for being classified as a cull. In year four, due to a severe codling moth infestation, codling moth-injured fruits were removed from each replicate during the growing season, the numbers recorded and added to the total cullage for that replicate at harvest. It was noted each season that many cull fruits at harvest time exhibited multiple defects any one of which would have been cause for cullage. As a result in year four cullage caused by leafroller alone was evaluated. Because of the large size of the experimental plots and field sorting at harvest, the fruit from plots being commercially harvested, harvested fruit being packed by different packing operations each year of the study and excessive damage in year four by the codling moth outbreak, total cullage rate assessment and comparison proved challenging.
**Pandemis pyrusana Populations and Parasitism**

**Pandemis pyrusana parasitism in buds** - At tight cluster to finger stage of development (approximately mid-April) 10 fruit buds were collected from each of 30 trees per plot. They were placed in labeled zip lock bags and transported to the lab for dissection and collection of larvae. The collected larvae were reared out and the number of those parasitized recorded. The parasitoid species reared out were identified as close to the species level as possible.

**Pandemis pyrusana infestation levels (spring and summer)** - At petal fall, during the 1st or 2nd week in May, 10 shoots high in the canopy were inspected on 30 trees per plot. These counts were continued at one-week intervals for three weeks. The number of active leafroller feeding sites per tree was recorded. The same procedure was repeated for the summer leafroller generation (mid-July to early August).

**Early spring Pandemis pyrusana parasitism in shoots** - In mid-May, when leafroller larvae were nearly mature but before pupation, 100 larvae from each plot were collected randomly from trees in each replicate, placed in labeled paper bags and brought to the laboratory for rearing. Larvae were placed in a clear plastic, 100 ml lidded cup with modified pinto bean diet for noctuids (Nobbs, 1997). They were maintained at room temperature until parasitoid or adult leafroller emergence. The rate of parasitism and parasitoid species was recorded. Parasitism rate was calculated by dividing the number of parasitoids to emerge by the number of larvae reared. Larvae dying of causes other than parasitism were not included in the calculation.

**Summer Pandemis pyrusana parasitism** - In late August, as leafroller larva were maturing but before pupation, 100 to 300 larvae were collected from each replicate, placed in labeled paper bags and returned to the laboratory for rearing. The rate of parasitism and parasitoid species was
recorded. This protocol was not preformed in the first year but was in the last three years of the study.

**Sentinel Obliquebanded Leafroller Parasitism**

Beginning in late June and continuing through mid-October, twenty sentinel 3rd-instar Obliquebanded Leafroller larvae were placed on each of 10 shoots (2 larvae per shoot) on a transect row of trees in each replicate. The shoots were flagged and larvae were retrieved in 10 days. Shoots for sentinel leafroller placement were selected for consistent location in the canopy (approximately chest to shoulder high), consistent vigor and evidence of new growth. Larvae recovered within their retreats were placed in cups in labeled bags and returned to the laboratory for rearing. The rate of parasitism and parasitoid species was recorded. Again larvae were placed in a clear plastic, 100 ml lidded cup with modified pinto bean diet for noctuids (Nobbs, 1997). They were maintained at room temperature until parasitoid or adult leafroller emergence. The rate of parasitism and parasitoid species was recorded. Parasitism rate was calculated by dividing the number of parasitoids to emerge by the number of larvae reared. Larvae dying of causes other than parasitism were not included in the calculation.

**Codling Moth, *P. pyrusana* and Obliquebanded Leafroller Trapping**

To monitor codling moth, *P. pyrusana* and obliquebanded leafroller adult populations, delta traps (Trece Inc., Salinas, CA) for containing a lure for each species were placed in the replicates at bloom or shortly thereafter. The traps were hung in the upper third of the tree canopy and there were two for each species. Ten mg load lures (Scenturian Inc., Clinton, WA) were used in the codling moth traps and 1 mg lures in the leafroller traps. Lures were replaced every 3 weeks during the spring and every 2 weeks in summer. Traps were checked twice weekly and the number of moths caught in each trap noted. Trap monitoring continued through September.
Codling Moth Injury to Fruit

To assess fruit damage caused by codling moth, we visually inspected fruits on randomly chosen trees in five sample rows of each plot. Apples from all levels of the tree canopy were included. This inspection was conducted in late June or early July, after summer generation egg hatch. The exposed side (to the outside of the canopy) of 10 fruits on each of 30 sample trees per plot was inspected for codling moth injury. The number of fruit with codling moth injury was recorded. This was done for all years of the experiment.

Secondary Insect Pest Populations

Aphids - Apple grain aphid, *Rhopalosiphum fitchii* (Sanderson), green apple aphid, *Aphis pomi* De Geer and rosy apple aphid, *Dysaphis plantaginea* Passerini populations were assessed during the growing season, beginning in late spring (first part of June) and running through mid-summer (early August). Five vigorous growing shoots in the upper canopy on 30 sample trees per plot were inspected every three weeks. The number of shoots with 5 or more leaves infested with aphids as well as the species was recorded. For analysis, data from individual sampling events were combined into two groups; spring and summer populations. Aphid predation was assessed by visually inspecting 50 aphid-infested shoots per replicate and counting the number of predators present.

Mullein bug, thrips, lygus and stinkbug - At the pink through full bloom stages of tree development (in early May) we conducted beating tray (limb tap) sampling to assess the densities of the mullen plant bug, thrips, lygus and stink bug. Thirty beating tray samples, two trays per tree (one black surface tray and one white surface tray for each tree), on 15 randomly chosen sample trees, were taken in each replicate. Uniformly selected branches were subjected to three firm taps each with the tray held underneath to catch dislodged arthropods. The number
of campylomma, lygus bug, thrips and stinkbug per tray per plot were recorded. Arthropods other than previously listed were also recorded. Beating tray sampling was conducted weekly for three consecutive weeks.

**White apple leafhopper** - In mid May and again in early August, white apple leafhopper (WALH) infestation levels were assessed by inspecting the underside of 5 leaves from each of 30 trees per plot. The number of nymphs per leaf was recorded.

**Western tentiform leafminer** - In late May or early June western tentiform leafminer (WTLM) was assessed by collecting 5 mid-shoot leaves from each of 30 trees per plot (150 leaf samples). If mines were scarce we collected only leaves with mines for up to 30 minutes per replicate to a maximum of 100 mines. Collected leaves were returned to the laboratory in labeled paper bags where the mines were dissected and the percent parasitism and parasitoid species recorded. Identical sampling was again conducted for the subsequent generations every three weeks from late June through mid-August.

**Phytophagous and Predatory Mites**

Populations of the phytophagous mites, McDaniel spider mite, *Tetranychus mcdanieli*, McGregor, two-spotted spider mite, *Tetranychus urticae*, Koch, European red mite, *Panonychus ulmi* (Koch) and the predaceous mites, *Typhlodromus occidentalis* and *Zetztalia mali* were assessed via the leaf collection and brushing technique. Five leaves from each of 10 trees per plot were collected. The leaf samples were brought to the laboratory where leaves were brushed. Active phytophagous and predatory mites were counted and recorded by species under 10x magnification. This procedure was repeated every three weeks from early June through early September.
Overwintering Arthropods

To assess overwintering diversity of the general arthropod population in the orchard 2.5cm wide, corrugated cardboard strips were placed around the base of 30 sample trees in each replicate. This served as an overwintering site for arthropods. The strips were secured to trees at their crown in mid-August. The bands were then collected in mid-October, stored in sealed plastic bags at 5.7 °C until January. The bands, still in plastic bags, were then removed from refrigeration, left at room temperature for a period of approximately one month and then examined for the presence of arthropods. Arthropods present were counted and categorized.

Analysis of Data

Data were subjected to analysis of variance, alpha 0.05. Data in percentages were transformed by the square root arcsin when appropriate (Davis, 2000; Snedecor and Cochran, 1976). Statistical analysis software, Statistix 7 (2000) was utilized.
CHAPTER THREE

LEAFROLLER POPULATIONS AND PARASITISM

Introduction

Leafrollers (Lepidoptera: Tortricidae), both native and imported, have become pests inhabiting commercial apple (*Malus domestica* Borkh) orchards in North America (Weires and Riedle, 1991). In apple orchards of Washington State the obliquebanded leafroller, *Choristoneura rosaceana* (Harris) and the pandemis leafroller, *Pandemis pyrusana* (Kearfoll) are the most prevalent and destructive species (Beers et al., 1993; Brunner et al., 2001). Washington State apple growers, like their counterparts in other parts of North America and around the world, are moving away from insecticide-based pest control strategies and toward the implementation of biologically or ecologically based pest management in integrated production systems (Gruys, 1982; Kuhlman, 1996; Prokopy et al. 1994). When broad-spectrum insecticides are reduced or eliminated from the orchard agroecosystem, changes in the arthropod complex can occur (Altieri, et al., 1993; Balazs et al., 1996; Beers and Brunner, 1999; Bostanian et al., 2001; Brown and Schmitt, 2001; Brown et al., 1988; Buban et al., 1996b; Ciglar, 1996; Costello, 1994; Gut et al., 1995; Hagley, 1978; Hesler et al., 1993; Jenser et al., 1999; Prokopy et al., 1980, Suckling et al., 1999; Trimble and Vickers, 2000). Insects that were previously classified as minor or secondary pests can become substantially more injurious. This was the case with leafrollers in Washington apple orchards that adopted pheromone-based mating disruption technology for the management of codling moth (*Cydia pomenella*) (Beers et al. 1993; Brunner et al. 1994; Warner, 1996a). In other instances pesticide use has induced a secondary pest species to become a key pest due to the elimination of natural control agents (Beers 1998; Flint and van den Bosch, 1981; Luna and House, 1990; National Research Council, 1996; Norlund, 1984).
As indirect pests, pandemis and obliquebanded leafrollers feed primarily on foliage and do not require fruit to complete their development nor do they preferentially seek fruit for feeding. However, it is common for larvae to attach leaves to fruit or use fruit clusters as sheltered feeding sites that can result in some level of fruit damage (Beers et al., 1993; Brunner, 1991).

*P. pyrusana* is usually a pest in established, bearing apple orchards (Brunner and Beers, 1990). The obliquebanded leafroller, a native and widely distributed North American species (Reissig, 1978) is most often (but not exclusively) a pest in newly planted and young orchards in Washington (Brunner and Beers, 1990). Obliquebanded leafroller was described as a prevalent and major pest in British Columbia apple orchards by Madsen (1984a) and Smirle (1993) and it is considered a major apple pest in New York (Onstad et al., 1985). Both leafroller species are polyphagous and have been collected from a diverse group of hosts (Brunner and Beers, 1990) although apple and rose have been described as their primary hosts (Mayer and Beirne, 1974b).

Leafroller control in the Pacific Northwest and elsewhere continues to be based on the use of conventional broad-spectrum insecticides. Because the life histories of the obliquebanded leafroller and *P. pyrusana* are essentially the same, separate control measures have not been necessary. It is recommended to target the overwintering larvae with delayed dormant oil/chlorpyriphos treatment just after they have left their hibernacula. To avoid disruption of integrated mite management and to minimize resistance development, later season broad-spectrum insecticide applications are discouraged, however, in-season azinphosmethyl applications to control codling moth have provided some level of leafroller control. The bacterial insecticide *Bacillus thuringinesis* (Bt) is often used to control leafrollers in late spring and summer. Brunner (1997b) recommended chlorpyriphos or encapsulated methylparathion for control of the summer leafroller generation when population densities exceeded 5% infested.
shoots. Other management tactics such as mating disruption have been explored or are considered to have potential (Anderson and Elliot, 1982; Brunner, 1997a; de Reed et al., 1985; Evenden et al., 1999; Knight and Turner, 1999; Knight et al., 2000; Waldstein and Reissig, 2001; Warner, 1996a; Willson and Trammel, 1980).

Reduction in the use of broad-spectrum pesticides is not the only cause for increased leafroller densities in orchards (Warner, 1997a). Resistance to several classes of insecticides by leafrollers has been reported in many areas around the world where tree fruits are grown. For example, the fruit tree leafroller, *Archips rosanus*, has developed resistance to diazinon in British Columbia (Alway, 1996b; Carriere et al., 1996; Croft, 1982; Lawson et al., 1997a; Madsen and Carty, 1977; Reissig et al., 1986; Vakenti et al., 1984; Waldstein et al., 1999). Brunner (1991, 1997b) reported evidence of leafroller resistance to organophosphate insecticides in Washington orchards.

Whether from reduced pesticide use, or increased resistance to insecticides, leafrollers in Washington orchards have assumed a premiere pest status (Beers et al., 1993; Knight et al., 1998). In light of the above plus the call for reduced pesticide use and dependence and the development of ecologically based pest management strategies (Benbrook, 1996; Hill, 1999; Lewis et al., 1997; National Research Council, 1996; Wiles et al., 1999) biological control of apple leafrollers is considered an alternative management strategy with potential (Beers et al., 1993; Brunner, 1996; Pfannensteil, 1997).

One leafroller parasitoid of particular interest is the eulophid wasp *Colpocyypes florus* (Warner, 1995; Brunner, 1991). Another parasitoid wasp thought to have potential to contribute to leafroller biocontrol is *Apanteles* sp. (Braconidae). Additionally, tachinids (Diptera: Tachinidae)
have the potential to be a valuable group of parasitoids for leafroller biocontrol (Beers et al. 1993).

Environmental manipulations can be used to augment or conserve natural enemy populations and activity (Norlund, 1984). This strategy generally involves utilizing the crop or surrounding vegetation as a field insectary to increase natural enemy densities or make them more efficient by reducing the distance they must migrate to find hosts. Such habitat manipulations are the means and mechanisms to achieve biodiversity and hopefully stability of pest populations (Altieri, 1994; Bugg and Pickett, 1998). Examples of this kind of habitat manipulation are common and include providing sources of alternate, supplementary or complimentary herbaceous or animal foods, enhancing refugia, nesting sites, overwintering sites, and modifying climates (Flint and van den Bosch, 1981; Norlund, 1984; Pedigo, 2002, Bugg and Picket, 1998). Cover crops in orchards have been and are currently used for such purposes and investigations into such ensue (Altieri, 1994; Altieri and Nickolls, 1999; Bugg and Waddington, 1994; Nickolls and Altieri, 2001; Wyss, 1995). Indeed farms with dominant perennial crop components, such as orchards, are considered semi-permanent ecosystems, more stable than annual plant systems, characterized by greater structural diversity and generally possessing greater potential for establishment of biological control agents especially when understory plant diversity is encouraged (Altieri, 1994; Huffacker and Messenger, 1976; Prokopy, 1994). Leguminous plants, such as alfalfa, are often considered for orchard cover and habitat diversification (Altieri, 1994; Brown and Schmitt, 1996; Rice et al., 1998; Smith et al., 1994). They are recognized as “stabilizing crops” used to improve soils and crop yields and to increase diversity of beneficials (Stary and Pike, 1999).
It may be that the combined effect of reduced broad-spectrum insecticide use coupled with appropriate habitat manipulations may create an environment where the level of leafroller biological control in Washington apple orchards can be increased. The objective of this study was to evaluate leafroller population development and biological control of leafrollers by parasitoids in an apple orchard with either an alfalfa cover a standard grass cover and in which mating disruption was used for codling moth control with no additional in-season insecticides.

**Materials and Methods**

This experiment was conducted from the spring of 1999 through winter of 2002 and was inclusive of four growing seasons. Plots for this experiment were established in a 3.12-hectare, 5th leaf, mature-bearing Fuji (BC 2/M9) apple block at East Wenatchee, Washington. It was in proximity to many commercial apple, cherry and pear orchards. Trees in the block were planted at a spacing of 1.2m X 3.96m for an approximate density of 1,977 trees per hectare. They were trained to a modified HYTEC system typified by a central axis, conical shape and aggressive lateral renewal (Barrett, 1992) and supported on an upright, 3-wire, 3m high, trellis. Portions of the experimental block bordered apple orchard, sweet cherry orchard and wild vegetation.

The 3.12-hectare block was divided into six contiguous plots varying in area from 0.49 to 0.57 hectare and containing from 1004 to 1056 trees each. Plots were configured to minimize borders with adjacent plots and to maximize distance between a designated, core-sampling area situated in the interior of each plot. At least 31.6m separated each plot core-sampling area from adjacent plot core sampling areas within the block. The core-sampling area for each plot, configured to be central to an individual plot, was approximately 0.12 ha in size. Additionally a ‘star’ configuration of sample trees (numbered 1-30) was delineated for each plot. The ‘star’ consisted of a transect row of trees extending from the north-south boundaries of each plot core sampling
area to the plot center with four arms originating at the plot center and radiating tangentially and equally from the transect row. A randomized block design was utilized for this experiment (Davis, 2000; Snedecor and Cochran, 1976). The three treatments each of alfalfa or grass covers were equally and randomly assigned to one of the six, approximately 0.5 hectare, plots so that there were three replications of the grass cover treatment, designated plots G1, G2, and G3, and three replications of the alfalfa cover treatment, designated plots A1, A2, and A3 (see Appendix A). Thus there were three replicate blocks; each containing two experimental cover treatments plots. The bi-species grass cover was representative of a standard orchard cover treatment in Washington and as such constituted the control for this study.

Both alfalfa and grass plots were sown with their respective cover cultivar on May, 21 1999, the initial year of the experiment. A standard grass orchard cover mix of perennial rye and red fescue was utilized for the grass cover treatment while ‘Vernal’, an older, drought tolerant, lower vigor cultivar, was utilized for the alfalfa cover treatment. A 1.52m wide, tree row, weed-free strip was maintained with glyphosate herbicide per standard orchard management practice. The orchard block was farmed utilizing standard practices with the exception of arthropod pest management. All plots were uniformly cultivated. Mating disruption was used for codling moth (Cydia pomonella) management. Isomate-C pheromone emitters were dispensed in the treatment plots at 500 emitters per hectare per standard recommendations and practice. This was considered a low or half emitter rate. Other than a single, delayed dormant superior oil application (at 11.3 liters/378 liters of water) no insecticide treatments were utilized in the plots for arthropod management during growing seasons. Carbaryl was used, per standard recommendation and practice, as a fruitlet thinner in the first two of the four experimental seasons (see appendix B).
The following procedures were used to assess *P. pyrusana* larvae infestation, parasitism of *P. pyrusana* and leafroller (*P. pyrusana* and obliquebanded) moth activity.

*P. pyrusana* larvae infestation

In the early spring, tight cluster to finger stage (pre-bloom) of tree development (approximately mid-April) infestation rate by overwintering *P. pyrusana* leafroller larvae was assessed by collecting ten fruit buds from each of 30 trees in each replicate. These 300 fruiting buds or clusters were examined in the laboratory for the presence or absence of larvae. Rate of infestation and parasitoid species reared were recorded.

At petal fall (usually about the first week of May), ten shoots high in the canopy were inspected on 30 trees per plot (300 shoots) and the observed number of active leafroller feeding sites per tree was recorded. These counts were conducted weekly for three consecutive weeks.

The above procedure was repeated in August for a summer generation infestation level estimation. Spring infestation levels were estimated for all four years of the study while summer infestations were estimated for the first and last years only (see results and discussion).

Overwintering *P. pyrusana* was estimated by trapping larvae seeking overwintering sites. 2.5cm wide, corrugated cardboard strips were placed around the base of 30 sample trees in each replicate. The strips were secured to trees at their crown in mid-August. The bands were then collected in mid-October, stored in sealed plastic bags at 5.7 °C until January. The bands, still in plastic bags, were then removed from refrigeration, left at room temperature for a period of approximately one month and then examined for the presence of leafrollers.
**P. pyrusana parasitism**

In the early spring, tight cluster to finger stage (pre-bloom) of tree development (approximately mid-April) parasitism of the overwintering *Pandemis pyrusana* leafroller larvae was assessed by collecting ten fruit buds from each of 30 trees in each replicate. These 300 fruiting buds or clusters were examined in the laboratory and any with larvae were placed in a clear plastic cup that contained an artificial diet (Nobbs, 1997). All larvae were reared in the laboratory at room temperature until they died or emerged as adult leafrollers or parasitoids. Rate of parasitism and parasitoid species reared were recorded.

In mid-May, when overwintering generation leafroller larvae were nearly mature but before pupation, 100 larvae within their retreats, from each plot, were collected and brought to the laboratory and reared to the adult stage as described above for the earlier overwintering larval sample. If larva were scarce we searched for 30 minutes per plot. In some instances we were unable to collect 100 larvae from each plot. As before the rate of parasitism and parasitoid species was recorded.

Parasitism of *P. pyrusana* larvae in the summer was assessed by collecting 100 - 300 larvae, within their webbed retreats, per plot and rearing them out. Collection times varied from mid to late summer. Collections in year one were made the last week in July, in year two the second week in September, in year three in August to early September and in year four early August. The rate of parasitism and parasitoid species was recorded.

**Adult leafroller moth activity**

Adult *P. pyrusana* and obliquebanded leafroller populations were monitored all four years of the study. Two delta traps (Trece) for each species were placed in the plots at bloom or shortly
thereafter. The traps were hung in the upper third of the tree canopy. Ten mg lures (Scenturian) were used in all traps. Lures were replaced every 3 weeks during the spring and every 2 weeks in summer. Traps were checked twice weekly and the number of moths caught in each trap recorded. Trap monitoring continued through September 7th.

Sentinel obliquebanded leafroller parasitism

Sentinel obliquebanded leafroller were utilized to further assess parasitoid activity and potential. Beginning in late June and continuing through mid-October twenty 3rd-instar sentinel obliquebanded leafroller larvae were set out on 10 flagged shoots of transect row trees in each plot and then retrieved 10 days later. Sentinel larvae were repeatedly set out and retrieved every ten days during this 3.5-month period. Two sentinel larvae were placed on each shoot. Shoots for sentinel leafroller placement were selected for consistent location in the canopy (approximately chest to shoulder high), consistent moderate vigor and evidence of new growth. Retrieved larvae, within their retreats, were brought to the lab for rearing out. The rate of parasitism and parasitoid species was recorded.

Parasitoid species

To identify the parasitoids reared from P. pyrusana and obliquebanded leafrollers I submitted specimens to the James Entomological Collection at Washington State University.

Data comparing treatments within a year were subjected to one-way analysis of variance; alpha 0.05. Percentage data were subject to square root arcsin transformation for analysis (Davis, 2000; Snedecor and Cochran, 1976). Statistical analysis software, Statistix 7 (2000) was utilized.
Results and Discussion

Parasitoid species

In addition to the eulophid *Colpoclypeus florus*, four different braconids were reared; two *Apantales* spp. and two *Bracon* spp. One of the *Apanteles* sp. is assumed to be *A. atar* (Beers et al., 1993). Conclusive identification at the species level is pending. For the purposes of reporting the level of parasitism by this group they are tabulated as Braconidae. The tachinid reared from leafrollers was identified as *Nemorillia pyste* (Walker). In this study no attempt was made to determine the ratio of parasitoid species reared from each leafroller species.

*P. pyrusana* populations and parasitism.

*P. pyrusana* larvae infestation.

Overwintering *P. pyrusana* infestation rates at tight cluster (mid-April) were assessed. In years one, three and four there was little difference (power of the test = 0.05, 0.09 and 0.18 respectively) in the density of leafrollers between cover crop treatments (Table 3.1). In year two, the alfalfa treatment infestation level was significantly greater than grass treatment levels though both were relatively low (F= 17.0; DF= 1, 4; $P= 0.014$). Populations of *P. pyrusana* were low in both cover treatments in year one, with only 0.43% of the flower buds infested in the alfalfa cover crop treatment. In the alfalfa treatment, *P. pyrusana* densities increased in year two to 2.4%, exploded to 42% in year three but subsided substantially in year four to 5.4%. The grass treatment followed a very similar pattern. Year one infestations levels were 0.89%, they declined in year two to 0.23%, and in year three rose similarly to populations in alfalfa treatment plots to 40% and in year four infestation levels dropped to 4.9%. As such overwintering *P.
"pyrusana" population measures for both treatments followed nearly identical paths (Figure 3.1). Populations peaked in year three, for both cover treatments, with nearly half of the flower clusters being infested. This was followed by a precipitous population decline in the spring of year four.

"Pyrusana" infestation levels were again assessed during the first three weeks in May, at petal fall, by examining shoots (Figure 3.2). "Pyrusana" populations increased dramatically, peaking in year three, and then dropping to substantially lower levels in year four for both cover crop treatments just as tight-cluster assessments had indicated. In the alfalfa treatment the percent of shoots infested per tree at the start of the study was 0.78% but rose to 19.77% in year two, 38.77% in year three and then fell to 12.92% in year four. In the grass treatment in year one the spring shoot infestation levels per tree were higher than in the alfalfa treatment, 0.33% shoots infested, but showed similar increase in year two, 18.77% and peaked at 57.77% in year three then declined again to 11.56% in year four. In the first two years infestation levels did not differ between the grass and alfalfa cover treatments (power of the test= 0.06 for year one and 0.05 for year two). However in year three the shoot infestation level for the grass treatment was significantly greater (57.77% of the shoots per tree) than for the alfalfa treatments (38.77%), (F= 11.88; DF= 1,4; P=0.026). In year four infestation levels were significantly greater for alfalfa plots (12.93%) than for grass plots (11.56%), (F= 17.56; DF= 1,4; P= 0.013). These differences did not seem of practical significance though (Table 3.2). These data certainly suggest that in the absence of broad-spectrum (or other) insecticide treatment "Pyrusana" populations can increase in dramatic fashion and that this can occur over a three-year period before some reduction is noted. It is not remotely clear from this study if the lower densities observed in year four represent some return to what could be classified as an equilibrium level but if this is the case it is certainly higher than would typically be tolerated in a commercial orchard under a pesticide-
Table 3.1. Mean percentage rate of buds infested by *P. pyrusana* at the tight cluster stage in plots with grass and alfalfa cover, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.43a</td>
<td>0.75</td>
<td>0.89a</td>
<td>0.19</td>
</tr>
<tr>
<td>2000</td>
<td>2.43a</td>
<td>0.83</td>
<td>0.23b</td>
<td>0.40</td>
</tr>
<tr>
<td>2001</td>
<td>40.67a</td>
<td>12.05</td>
<td>40.00a</td>
<td>10.13</td>
</tr>
<tr>
<td>2002</td>
<td>5.43a</td>
<td>1.19</td>
<td>4.97a</td>
<td>4.36</td>
</tr>
</tbody>
</table>

Means were transformed for analysis, those followed by the same letter are not significantly different (*P* = 0.05). See F values cited in the text. Treatments were compared for each year separately.

Figure 3.1 Mean percentage rate of shoots infested by *P. pyrusana* in the spring (May) at petal fall stage in plots with alfalfa and grass, by year.
Table 3.2. Mean percentage rate of shoots infested by *P. pyrusana* in the spring (May) at petal fall stage in plots with alfalfa and grass, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.78a</td>
<td>0.30</td>
<td>0.33a</td>
<td>0.23</td>
</tr>
<tr>
<td>2000</td>
<td>19.77a</td>
<td>1.16</td>
<td>18.77a</td>
<td>1.36</td>
</tr>
<tr>
<td>2001</td>
<td>38.77b</td>
<td>1.18</td>
<td>57.77a</td>
<td>2.34</td>
</tr>
<tr>
<td>2002</td>
<td>12.93a</td>
<td>1.13</td>
<td>11.56b</td>
<td>1.05</td>
</tr>
</tbody>
</table>

Means were transformed for analysis, those followed by the same letter are not significantly different (*P* = 0.05). See F values cited in the text. Treatments were compared for each year separately.

Figure 3.2. Mean per plot percentage rate of shoots infested by *P. pyrusana* in the spring (May) at petal fall.
based management system. That low tolerance, however, is not necessarily an indication of a economically consequential infestation level. As such, whether the higher population level observed in year four is genuinely economically compromising is a question.

Data to estimate summer shoot infestations were collected in the first year and the last year only. I did not collect data in years two and three because foliar damage from the previous generation was extensive and active leafroller retreats at this time were extremely numerous. Additionally extensive foliage feeding damage by the cutworm, *Lacanobia subjuncta*, and wind damage exacerbated our inability to distinguish leafroller retreats; it was impossible to determine exclusive summer generation leafroller infestation. In these two seasons (years two and three) virtually every shoot had evidence of leafroller infestation. However, year one, summer leafroller shoot infestation levels were greater for both alfalfa and grass cover treatments than infestation levels in year four, further substantiating the decline in *P. pyrusana* population levels (Figure 3.3). Infestation levels at this time were not different (power of the test = 0.06 for year one and 0.06 for year four) between treatments in either year one or year four (Table 3.3).

There were no differences in overwintering leafroller trap catch between cover treatments in any year of this study (power of the test = not able to calculate, 0.05, 0.06 and 0.05 for years one, two, three and four respectively), (Table 3.4). The greatest numbers of overwintering leafrollers were detected in year two when an average of 39.33 overwintering leafrollers were collected per plot from grass treatment plots and 29.80 from alfalfa treatment plots. This sharp increase in overwintering leafroller, from the year before may have been, in retrospect, indicative of the huge leafroller population to come in the following (year three) growing season. Thus overwintering trap catch may be a valuable predictive tool. Mean per plot overwintering leafroller trap catch declined
Table 3.3. Mean percentage rate of shoot infestation by summer generation *P. pyrusana* in August for plots of alfalfa or grass cover, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>56.67a</td>
<td>0.97</td>
<td>43.33a</td>
<td>0.97</td>
</tr>
<tr>
<td>2002</td>
<td>21.48a</td>
<td>0.55</td>
<td>22.59a</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Means were transformed for analysis, those followed by the same letter are not significantly different (*P* = 0.05). Treatments were compared for each year separately.

Figure 3.3. Mean percentage rate of shoot infestation by summer generation *P. pyrusana* in August for plots of alfalfa or grass cover, by year.
greatly in year three to 13.0 in grass treatment plots and 11.67 in alfalfa treatment plots, then to 2.0 in alfalfa treatment plots and 1.33 in grass treatment plots in the final year (four) of the study (Figure 3.4). The fact that year four overwintering leafroller measures were so low (approaching the nil levels of year one) further supports the notion that the leafroller populations in all treatment plots of the test block declined greatly during the fourth year growing-season.

If the large year two trap catch was indeed indicative of the large increase in leafroller populations observed in the year three growing season and the near 60% decrease in year three overwintering leafroller trap catch (for both cover crop treatments) indicated the much lower year four leafroller population then the very low year four overwintering trap catch likely indicates a substantially reduced leafroller population for what would have been the fifth year of the insecticide-free orchard environment. It would seem that the decline in the overwintering leafroller population further indicates a genuine lowering of this pest’s population level. Again the question remains, does this provide a better chance for biological control to be achieved and to maintain stabilized, low level pest populations?

**P. pyrusana parasitism**

Early spring (tight-cluster stage) parasitism of overwintering *P. pyrusana* was low throughout the experiment. In no year was parasitism significantly greater (power of the test = data all zeros, 0.05, 0.055 and 0.14 for years one, two, three and four respectively) for one treatment or the other (Table 3.5). Parasitism rates at this time were nil for both treatments in year one. In year two in the grass treatment parasitism was at 12.5% but that high rate constituted only one larva parasitized out of eight. In year three, when the population
Table 3.4. Mean number of overwintering leafrollers caught in cardboard band traps in alfalfa and grass cover plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.00a</td>
<td>0.00</td>
<td>0.00a</td>
<td>0.00</td>
</tr>
<tr>
<td>2000</td>
<td>29.00a</td>
<td>12.12</td>
<td>39.33a</td>
<td>27.42</td>
</tr>
<tr>
<td>2001</td>
<td>11.67a</td>
<td>3.51</td>
<td>13.00a</td>
<td>11.00</td>
</tr>
<tr>
<td>2002</td>
<td>2.00a</td>
<td>1.0</td>
<td>1.33a</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). Treatments were compared for each year separately.

Figure 3.4. Mean number of overwintering leafrollers caught in cardboard band traps in alfalfa or grass cover plots, by year.
peaked, low rates of parasitism were again detected for both grass (2.3%) and alfalfa (1.8%) treatments. In year three, two of the three alfalfa treatments had both the lowest and highest parasitism rates of all six plots. In year four, parasitism in the alfalfa treatment was 8.16% while for the grass treatment no parasitism was detected (Figure 3.5). Only Braconidae were reared from *P. pyrusana* in all treatments and in all years. In year three, when *P. pyrusana* densities peaked, Braconidae were retrieved from all plots. In the final year of the study parasitoids were reared only from leafroller larvae found in the alfalfa treatments at this sampling time.

For alfalfa treatments, parasitism increased each year and achieved the highest level of parasitism for either treatment (excluding the year two grass treatment), in any year, during the fourth year of the experiment while grass treatment parasitism rates remained fairly constant and lower overall. This may indicate that the alfalfa cover modestly encouraged parasitoid presence and activity. However the alfalfa cover certainly did not explicitly distinguish itself as particularly or consistently conducive to higher levels of parasitoid activity or leafroller parasitism in the spring. The increased spring parasitism rates in alfalfa treatment plots, though not significantly different from grass plots may indicate the possibility of slightly enhanced parasitism in alfalfa-covered plots.

Later, when overwintering *P. pyrusana* larvae were mature but before pupation (in mid-May) parasitism rates were again assessed (Table 3.6). Rates of parasitism were calculated based on surviving collected larvae. Some collected larvae died of other undetermined causes. Data for year one were not included in the analysis because larvae collection occurred too late, missing the overwintering generation. As such only three years of data are available for comparison. Overall, parasitism rates at this time were higher than for the early spring samples. Parasitism
Table 3.5. Mean percentage rate of *P. pyrusana* parasitism at the tight-cluster stage of tree development (April) in plots of alfalfa or grass cover, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th># parasitized/total collected</th>
<th>S.D.</th>
<th>Grass</th>
<th># parasitized/total collected</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.00a</td>
<td>0/0</td>
<td>0.00</td>
<td>0.00a</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>2000</td>
<td>0.00a</td>
<td>0/0</td>
<td>0.00</td>
<td>12.50a</td>
<td>1/80</td>
<td>0.35</td>
</tr>
<tr>
<td>2001</td>
<td>1.87a</td>
<td>7/374</td>
<td>0.13</td>
<td>2.31a</td>
<td>9/390</td>
<td>0.15</td>
</tr>
<tr>
<td>2002</td>
<td>8.16a</td>
<td>4/49</td>
<td>0.27</td>
<td>0.00a</td>
<td>0/0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Means were transformed for analysis, those followed by the same letter are not significantly different (*P* = 0.05). Treatments were compared for each year separately.

Figure 3.5. Mean percentage rate of *P. pyrusana* parasitism at the tight-cluster stage of tree development (April) in plots of alfalfa or grass cover, by year.
rates in year two were 3.26% for the alfalfa treatment and 4.90% for the grass treatment. The following year (three), when leafroller population levels were highest, parasitism rates for the alfalfa treatment were 12.93% and for the grass treatment 7.66%. In the fourth year of the study alfalfa treatment parasitism rate rose to 18.75%, the single highest rate for all three years regardless of treatment (Figure 3.6). It was a rate significantly greater than that for grass plots in the same year (F= 117.92; DF= 1,4; P< 0.001). Year three alfalfa plot parasitism rates were also significantly greater (F= 2175.07; DF= 1,4: P< 0.001) that for grass plots. Conversely grass treatment plots exhibited significantly (F= 114.76; DF= 1,4; P< 0.001) greater parasitism in year two. In years one, two and three there was no difference in cover treatments (power of the test = 0.08, 0.10, and 0.06 for years one, two and three respectively).

The grass treatment parasitism rate of 5.55% in year four was similar to year two and three rates. Thus grass parasitism rates seemed to remain more or less static while alfalfa plot parasitism increased rather substantially. As was the case for parasites reared from larvae collected from tight clusters, for all years and both treatments only Braconidae were reared from larvae collected at this time.

Collection timing for summer generation *P. pyrusana* parasitism assessment was somewhat inconsistent between years, which likely influenced rates of parasitism observed. Generally later collections demonstrated higher rates of parasitism. Collections varied from late July (year one), early August (years three and four), to early September (year two). Parasitism rates for this sampling were lowest in the first year and last year of the study for the alfalfa treatment but for the grass treatment the first two years indicated the highest parasitism rates at this time (Table 3.7, Figure 3.7). Year two *P. pyrusana* summer generation parasitism rates for the alfalfa
Table 3.6. Mean percentage rate of *P. pyrusana* parasitism at petal fall (mid-May) in alfalfa or grass plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th># parasites/total collected</th>
<th>S.D.</th>
<th>Grass</th>
<th># parasites/total collected</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>3.26b</td>
<td>2/61</td>
<td>0.17</td>
<td>4.90a</td>
<td>3/61</td>
<td>0.21</td>
</tr>
<tr>
<td>2001</td>
<td>12.93a</td>
<td>34/262</td>
<td>0.33</td>
<td>7.66b</td>
<td>21/274</td>
<td>0.26</td>
</tr>
<tr>
<td>2002</td>
<td>18.75a</td>
<td>12/64</td>
<td>0.39</td>
<td>5.55b</td>
<td>3/54</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Means were transformed for analysis, those followed by the same letter are not significantly different ($P = 0.05$). See F values cited in the text. Treatments were compared for each year separately.

Figure 3.6. Mean percentage rate of *P. pyrusana* parasitism at petal fall (mid-May) in alfalfa or grass plots, by year.
Table 3.7. Mean percentage of summer generation *P. pyrusana* parasitism for alfalfa or grass plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th># parasitized/total collected</th>
<th>S.D.</th>
<th>Grass</th>
<th># parasitized/total collected</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>41.66a</td>
<td>6/14</td>
<td>38.18</td>
<td>85.00a</td>
<td>17/20</td>
<td>13.18</td>
</tr>
<tr>
<td>2000</td>
<td>93.33a</td>
<td>24/26</td>
<td>11.54</td>
<td>97.33a</td>
<td>21/22</td>
<td>4.43</td>
</tr>
<tr>
<td>2001</td>
<td>51.43a</td>
<td>45/87</td>
<td>2.48</td>
<td>52.47a</td>
<td>38/72</td>
<td>26.75</td>
</tr>
<tr>
<td>2002</td>
<td>42.59a</td>
<td>22/52</td>
<td>8.76</td>
<td>36.86a</td>
<td>21/57</td>
<td>6.04</td>
</tr>
</tbody>
</table>

Means were transformed for analysis, those followed by the same letter are not significantly different (*P* = 0.05). Treatments were compared for each year separately.

Figure 3.7. Mean per plot percentage of summer generation *P. pyrusana* parasitism.
treatment were more than double that of year one. They then dropped in year three and again in year four to a level very close to that of year one. Grass treatment parasitism levels did not follow the same course. For the grass treatment parasitism was very high the first two years and then declined in year three and again to its lowest level (36.86%) in year four. Both treatments had relatively low levels of summer time parasitism in the fourth year of the experiment, which coincided with the dramatic decline in *P. pyrusana* populations.

The extremely high parasitism rates, especially in year two of the study, may be partly attributable to sample timing. It seems sampling may have been conducted when few of summer generation *P. pyrusana* larvae were present and these few larvae were likely subject to intense parasitoid pressure. In no year was summer generation parasitism significantly different between cover crop treatments (power of the test = 0.08, 0.05, 0.06 and 0.05 for years one, two, three and four respectively).

In year one, only tachinid parasitoids were reared from collected leafroller larvae. Year one was the earliest sampling. In subsequent years Braconidae were, by far, the dominant parasitoid species reared out at this time. In year two only Braconidae were reared from larvae collected from the grass treatment plots. From alfalfa treatment plots Braconidae represented 95.8% of parasitoids (n= 23); one tachinid was reared. In year three alfalfa treatment yielded 97.5% Braconidae (n= 42), 1.6 % tachinids (n= 2) and 0.8 % *C. florus* (n= 1). Grass treatment plots yielded 83.6% Braconidae (n= 38), 15.6% tachinids (n= 19) and 0.8 % *C. florus* (n= 1). In year four only Braconidae (n= 22) were reared from alfalfa treatment larvae. In grass treatments 95.5% Braconidae (n= 20) and 4.5% tachinids (n= 1) were reared. It was thought that *C. florus* parasitism would increase in the absence of broad-spectrum insecticides over time but the duration of this experiment was too limited or the location too isolated to make that
determination. Presence of *C. florus*, at this time, albeit minimal, again supports the notion that it will only contribute to later season biological control of leafrollers unless successfully augmented for spring presence and activity (Evenhuis, 1974; Nobbs, 1997).

The sharp and dramatic decline in *P. pyrusana* populations, in both treatments, cannot be attributed largely or exclusively to parasitism. A granulovirus (GV), as reported by Pfannenstiel and Brunner (2002), may have been largely responsible. Confirmation that *P. pyrusana* larvae were infected with this virus was made via evaluation of symptoms in consultation with a USDA insect pathologist (L. Lacy, 2002). Unfortunately samples retained for bioassay and definitive evaluation were inadvertently disposed of. Lacy et al., (2001) discuss the potential of granuloviruses for the biological control of lepidopteran pests. Additionally, generalist predators may have contributed to *P. pyrusana* biological control in test plots (Bostanian et al., 1984) though I made no attempt to quantify their presence or activity and thus have no substantive supporting data. Anecdotal evidence however indicated that spiders (Araneae) and earwigs, *Forficula auricularia* (Linnaeus) became increasingly prevalent. In year four it seemed that they became particularly abundant and were readily found on trees in all plots. It was common to find a spider or earwig in a leafroller retreat. We did not attempt to identify spider species or quantify the populations of spiders or earwigs. Miliczky and Calkins (2002) said that spiders, feeding on both leafroller eggs and larvae in apple orchards, might contribute substantially to natural control of leafrollers. As such these generalist predators may also have contributed to the collapse of the leafroller populations in test plots. It would be valuable to assess their populations and impact on leafroller populations. The precipitous decline in *P. pyrusana* populations in year four may indicate a lowered pest level after the initial surge that followed the elimination of broad-spectrum insecticides. This suggests that three seasons were necessary for this adjustment to occur and also that the parasitoid population increase lagged behind leafroller population
increase for a year, at least. Despite no increase in parasitism levels additional decline of *P. pyrusana* populations may have been at hand but the cessation of this experiment, after year four precluded further measurement.

**Parasitism of sentinel obliquebanded leafroller**

To further characterize parasitoid activity and potential, sentinel obliquebanded leafroller larvae were set out on shoots and collected approximately 10 days later throughout the growing season. In general parasitism rates did not increase over the duration of the study; in fact for the alfalfa treatment parasitism was lowest in the final year and for grass final year parasitism was nearly that of year one (Figure 3.8). Additionally sentinel obliquebanded leafroller parasitism only differed significantly (albeit not substantially) between cover treatments in year four of the study (Table 3.8) when grass plot parasitism was greater than alfalfa plots (*F* = 4.77; *DF* = 1, 52; *P* = 0.033), (power of the test = 0.93, 0.99 and 0.15 for years one, two and three respectively). It is not likely that this difference represents anything of practical significance. In year one the overall parasitism rate for the entire season was 38.52% for alfalfa and 26.41% for grass treatments. Parasitism rates for any given 10-day period varied greatly. I noted that, similar to *P. pyrusana* parasitism, the highest parasitism rates generally seemed to correspond to lower larvae retrieval rates. Very often there were great differences in parasitism rates between replicated plots in a treatment. Interestingly, in year one, only tachinids were reared from sentinel obliquebanded leafroller larvae. It was not until year two that Braconidae and *C. florus* were detected.

In year two I started setting out and collecting sentinel obliquebanded leafroller larvae a few weeks earlier. In both treatments parasitism of sentinel larvae in the 3rd week in June was by tachinids only. Overall year two parasitism rates for the alfalfa treatment was 47.04% and for the grass treatment 43.24% (Table 3.8). These were the highest total season parasitism rates of
the four-year experiment. Again maximum and minimum parasitism rates varied greatly though slightly more so for grass (high of 86% and low of 8%) than for alfalfa (high of 86% and low of 20%). In year two I did not see any particular pattern between larvae retrieval rates and parasitism levels. Early season parasitism was again exclusively by tachinids. Braconidae appeared (in alfalfa only) one month earlier (end of July) than in 1999. In grass Braconidae did not appear for another three weeks. Similarly *C. florus* appeared one month earlier (end of August) than the previous year and was present in both grass and alfalfa treatments by the 1st week of September. At this time tachinids, Braconidae and *C. florus* were present simultaneously in both grass and alfalfa treatments. This generally persisted for the next two weeks during which time *C. florus* parasitism rates increased. By the third week of September, at the peak level of seasonal parasitism (86% for both alfalfa and grass), *C. florus* accounted for 64% (n=18) of parasitism in alfalfa and 43% (n=3) in grass. In the 4th week of September (the last set of sentinel larvae) parasitism rates were 56% for alfalfa and 75% for grass with no tachinids detected and only one Braconidae reared from an alfalfa plot larva. Four *C. florus* were reared from alfalfa plot and 9 from grass plot sentinels at this time.

In year three the overall percent parasitism declined from second season highs to 32.42% for alfalfa and 33.50% for grass, down from 47.03% and 43.24% respectively (Table 3.8). This was the same year that *P. pyrusana* populations peaked at extremely high levels. It may be that parasitoids preferentially attacked *P. pyrusana* instead of sentinel obliquebanded leafroller. Thus data for obliquebanded leafroller parasitism may not necessarily reflect changes in *P. pyrusana* populations and potential parasitism.

Likewise the highest single set levels of parasitism in this year (three) did not approach those of previous years. The highest level of parasitism in alfalfa (65%) and grass (53%) occurred in the
Table 3.8. Overall mean seasonal percentage rate of sentinel obliquebanded leafroller parasitism for alfalfa or grass plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th># parasitized /total collected</th>
<th>S.D.</th>
<th>Grass</th>
<th># parasitized /total collected</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>38.52a</td>
<td>34/88</td>
<td>38.55</td>
<td>26.41a</td>
<td>41/155</td>
<td>32.38</td>
</tr>
<tr>
<td>2000</td>
<td>47.04a</td>
<td>108/229</td>
<td>36.38</td>
<td>43.24a</td>
<td>73/168</td>
<td>29.07</td>
</tr>
<tr>
<td>2001</td>
<td>32.42a</td>
<td>86/265</td>
<td>15.86</td>
<td>33.50a</td>
<td>85/253</td>
<td>22.28</td>
</tr>
<tr>
<td>2002</td>
<td>27.09b</td>
<td>61/225</td>
<td>13.70</td>
<td>29.19a</td>
<td>71/243</td>
<td>11.08</td>
</tr>
</tbody>
</table>

Means were transformed for analysis, those followed by the same letter are not significantly different ($P = 0.05$). See F values cited in the text. Treatments were compared for each year separately.

Figure 3.8. Overall mean seasonal percentage rate of sentinel obliquebanded leafroller parasitism for alfalfa or grass plots, by year.
1st week of July (the first sentinel larvae set). At this time tachinids were the primary parasitoids but Braconidae were reared from larvae set out in an alfalfa plot. The detection of Braconidae occurred three weeks earlier than the previous year and over five weeks earlier than in 1999. The very next larvae set (2nd week in July) yielded the lowest parasitism rates for both treatments. After that parasitism rates for both treatments generally and fairly equally rose with a slight dip in mid-September. The lowest parasitism levels occurred generally at the same time (within a two week period) for both treatments during years two and three suggesting some degree of consistency between treatments and no discernable effect of cover. Again, as in the previous years, early season parasitism was preponderantly due to tachinids. In grass treatments, during mid and later July Braconidae accounted for half (n=3) of the parasitism while disappearing in alfalfa during this same period. By the 2nd week of August Braconidae became the dominant parasitoid detected in both treatments. Consistent with the previous season but two weeks earlier than 1999, *C. florus* was reared from sentinel larvae at the end of August in year three. They came exclusively from alfalfa treatment plots. Simultaneously tachinids began to decline and became absent by the 1st week of September while both Braconidae and *C. florus* were detected in both treatments. For the last sampling period (3rd week of September) *C. florus* exclusively accounted for a 43% parasitism rate (n=6) in alfalfa and a 29% parasitism rate (n=4) in grass.

In year four overall parasitism levels declined further to 27.09% in the alfalfa treatment and 29.19% in the grass treatment. These were the lowest rates of parasitism except for grass in year one. Sentinel obliquebanded leafroller retrieval rates were generally relatively low in this last year of the study. Several times as few as five larvae were retrieved from a set of 20 in a plot. I
noted many spiders and earwigs in empty retreats when searching for sentinel larvae and as such it may be that increased predation by these arthropods caused some leafroller mortality.

A strongly evident trend between years was the early season (late spring) presence and dominance of the tachinid parasitoid, the mid-season peak of Braconidae and the later season occurrence and dominance of *C. florus* (Table 3.9). Obviously *C. florus*, as is consistent with conventional thinking (Brunner, 1994; Evenhuis, 1974) was not present in the orchard to parasitize leafrollers in the spring either because it does not overwinter in or near the orchard or because of a host preference. *C. florus* pattern of appearance as a late season parasitoid was similar between *P. pyrusana* and sentinel obliquebanded leafroller. The substantial early and mid-season presence of tachinid parasitoids suggests that they might be enhanced to achieve higher levels of spring-time leafroller parasitism. In contrast Braconidae were the dominant spring natural enemy parasitizing *P. pyrusana* when tachinids were scarce. This might suggest some level of tachinid preference for obliquebanded leafroller or a specialization though sample timing (early spring – vs. – late spring) might affect the apparentness of Braconidae (Figure 3.9). Brunner et al. (2001) demonstrated a rather profound sensitivity of *C. florus* to carbaryl. It is very likely that the carbaryl used as a fruit-thinning agent exerted an adverse effect on spring *C. florus* and possibly other parasitoids especially the tachinids and Braconidae in the orchard. The elimination of carbaryl as a thinning agent in late spring and early summer could be an important step in conserving parasitoids and other natural enemies in apple orchards. This speculation, however, was not strongly supported when we compared *C. florus* detection from sentinel obliquebanded leafroller larvae set out in a block (organic transition) in which carbaryl was not used as a fruitlet thinning agent (year three and four only). However *C. florus* did parasitize sentinel obliquebanded leafrollers in the organic transition block in July and not in the cover crop treatment blocks that same month. Additionally percent parasitism by *C. florus* was higher
Table 3.9. Percent parasitism of sentinel obliquebanded leafroller by parasitoid species, per month.

<table>
<thead>
<tr>
<th></th>
<th>Tachinidae</th>
<th></th>
<th>Braconidae</th>
<th></th>
<th>C. florus</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alfalfa</td>
<td>-</td>
<td>33.3%</td>
<td>31.8%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>grass</td>
<td>-</td>
<td>14.7%</td>
<td>20.0%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>July</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alfalfa</td>
<td>30.0%</td>
<td>20.5%</td>
<td>24.7%</td>
<td>8.6%</td>
<td>0%</td>
</tr>
<tr>
<td>grass</td>
<td>(60/10/3)</td>
<td>(120/39/8)</td>
<td>(120/97/24)</td>
<td>(180/58/5)</td>
<td>(120/39/4)</td>
</tr>
<tr>
<td>Aug.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alfalfa</td>
<td>6.5%</td>
<td>29.3%</td>
<td>8.6%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>grass</td>
<td>(240/185/12)</td>
<td>(120/41/12)</td>
<td>(120/105/9)</td>
<td>(120/37/7)</td>
<td>(120/41/5)</td>
</tr>
<tr>
<td>Sep.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>alfalfa</td>
<td>64.2%</td>
<td>16.1%</td>
<td>0%</td>
<td>2.8%</td>
<td>0%</td>
</tr>
<tr>
<td>grass</td>
<td>(120/28/18)</td>
<td>(120/93/15)</td>
<td>(120/54/9)</td>
<td>(180/72/2)</td>
<td>(120/93/1)</td>
</tr>
<tr>
<td></td>
<td>34.6%</td>
<td>16.6%</td>
<td>0%</td>
<td>4.2%</td>
<td>0%</td>
</tr>
<tr>
<td></td>
<td>(120/26/9)</td>
<td>(120/54/9)</td>
<td>(180/71/3)</td>
<td>(120/54/3)</td>
<td>(120/79/9)</td>
</tr>
</tbody>
</table>

Note: Month indicates collection timing. When multiple collections were done in one month, data were combined and averaged; - indicates no collection. For 1999 and 2001 sentinel were not set out until late June so collection began in July. Numbers in parentheses below % parasitism are, sequentially, (number set out/number retrieved/number parasitized). Al = alfalfa, gr= grass.
Figure 3.9 Average percent total parasitism of sentinel obliquebanded leafroller by parasitoid per treatment for all years.
Table 3.10. Percent parasitism of sentinel obliquebanded leafrollers by *C. florus* for the months of July, August and September comparing alfalfa and grass cover crop treatments plots with an organic transition plot.

<table>
<thead>
<tr>
<th>Month</th>
<th>Alfalfa</th>
<th>Grass</th>
<th>Organic</th>
</tr>
</thead>
<tbody>
<tr>
<td>July</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>n=2/26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>August</td>
<td>2.8</td>
<td>2.4</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>n=3/107</td>
<td>n=2/83</td>
<td>n=2/80</td>
</tr>
<tr>
<td>September</td>
<td>23.8</td>
<td>22.2</td>
<td>15.2</td>
</tr>
<tr>
<td></td>
<td>n=15/63</td>
<td>n=16/74</td>
<td>n=12/80</td>
</tr>
</tbody>
</table>
overall for the July, August and September (Table 3.10) in the organic transition block. These were the first seasons in which carbaryl was not used in the organic transition block so parasitoid populations may not have built up to levels one might otherwise expect.

Overall parasitism levels were greater in year two than for year one, year three or year four. It may be that the endemic leafroller populations in the experimental plots eclipsed parasitoid population increases during the summer of year two so that parasitoid populations lagged substantially behind during years three and four thus reducing overall rates of parasitism in these years.

**Adult *P. pyrusana* and obliquebanded leafroller populations**

Adult *P. pyrusana* and obliquebanded leafrollers were monitored by pheromone baited delta trap catch (Tables 3.11 and 3.12). For both, first and second generations trap catch generally rose steadily for the first three years and then declined sharply in year four. The greatest first generation weekly mean trap catch for *P. pyrusana* occurred in year three for both alfalfa and grass treatments; they were approximately four times greater than weekly mean trap catches at the beginning of the study. In no year was first generation trap catch different between treatments (power of the test = 0.05, 0.05, 0.36 and 0.06 for years one, two three and four respectively). Second-generation trap catch was significantly greater for alfalfa plots ($F= 15.10; DF= 1,4; P= 0.017$) in year three. For other years there was no difference between treatments (power of the test = 0.06, 0.10 and 0.05 for years one, two and four respectively). Mean weekly *P. pyrusana* trap catch for year four was greatly reduced from the overall high catches of year three and were not very much greater than that in year one (Figure 3.10). The rise and decline of
Table 3.11. Mean weekly, first and second generation, adult male *P. pyrusana* moths caught in sticky wing traps hung in the tree canopy in alfalfa and grass plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>1&lt;sup&gt;st&lt;/sup&gt; generation</th>
<th>2&lt;sup&gt;nd&lt;/sup&gt; generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>alfalfa</td>
<td>S.D.</td>
</tr>
<tr>
<td>1999</td>
<td>17.56a</td>
<td>2.65</td>
</tr>
<tr>
<td>2000</td>
<td>63.33a</td>
<td>3.59</td>
</tr>
<tr>
<td>2001</td>
<td>126.13a</td>
<td>12.86</td>
</tr>
<tr>
<td>2002</td>
<td>51.80a</td>
<td>3.64</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different (*P* = 0.05). Each generation was analyzed separately. Treatments were compared for each year separately.

Figure 3.10 Mean weekly, per plot, adult *P. pyrusana* trap catch.
adult *P. pyrusana* catch in pheromone traps coincided with the rise and collapse of *P. pyrusana* larvae populations discussed above. Mean weekly adult obliquebanded leafroller trap catch, for both generations one and two, was modest in every year of the study indicating, as expected, very low obliquebanded leafroller populations in the mature orchard block (Beers et al., 1993). There were no differences between treatments in any year for either generation (for first generation- power of the test = 0.05, 0.05, 0.54, and 0.07 for years one, two, three and four respectively; for second generation- power of the test = 0.29, 0.05, 0.056, and 0.07 for years one, two, three and four respectively). Adult obliquebanded leafroller populations were highest in the last year of the study, probably because of escaped sentinels (Figure 3.11).

**Fruit cullage from leafrollers**

Damage to fruit from leafrollers increased annually for the first three years of the study. In the last year, leafroller damage decreased dramatically (Table 3.13). For the alfalfa treatment leafroller damage to fruit was 1/3 that of the previous year and nearly approached year one levels. For the grass treatment, leafroller damage to fruit year four was nearly 1/3 less than in the previous season and half of that in year one. The three-year increase in fruit leafroller damage and dramatic fourth year decline reflected leafroller population levels observed. In year four total cullage with leafroller damage was estimated at 17 % and 18 % for alfalfa and grass treatments respectively. This measure reflected any culled apple with leafroller damage. In all years I noted that many cull apples had multiple defects, any one of which would have resulted in the fruit being discarded. As such, in the last year of the study I estimated the percent cullage due exclusively to leafroller damage. This estimation was derived from evaluation of field-culled apples at harvest time. For the alfalfa treatment it was estimated that 8.6 % of culled fruit suffered leafroller damage exclusively and for the grass treatment 9.0 %. It is generally accepted
Table 3.12. Mean weekly, first and second generation, adult male obliquebanded leafroller moths caught in sticky wing traps hung in the tree canopy for alfalfa and grass cover plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>1st generation</th>
<th>2nd generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>alfalfa</td>
<td>S.D.</td>
</tr>
<tr>
<td>1999</td>
<td>0.47a</td>
<td>0.82</td>
</tr>
<tr>
<td>2000</td>
<td>0.00a</td>
<td>0.00</td>
</tr>
<tr>
<td>2001</td>
<td>1.60a</td>
<td>1.11</td>
</tr>
<tr>
<td>2002</td>
<td>6.13a</td>
<td>7.68</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). See F values cited in the text. Each generation was analyzed separately. Treatments were compared for each year separately.

Figure 3.11. Mean weekly, per plot, adult obliquebanded leafroller trap catch.
Table 3.13. Yield and cullage from all causes and from insect and leafroller damage.

<table>
<thead>
<tr>
<th>Year</th>
<th>Area</th>
<th>Average total yield (bins)/plot</th>
<th>Average total cullage (bins)/plot</th>
<th>% cullage-all causes</th>
<th>% of culls with insect damage</th>
<th>% of culls with leafroller damage</th>
<th>Cullage-bins/acre with leafroller damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>af</td>
<td>40.3 bins</td>
<td>12.9 bins</td>
<td>31.3 %</td>
<td>36.0 %</td>
<td>11.3 %</td>
<td>1.5 bins</td>
</tr>
<tr>
<td></td>
<td>gr</td>
<td>31.3 bins</td>
<td>10.5 bins</td>
<td>33.5 %</td>
<td>56.0 %</td>
<td>33.0 %</td>
<td>3.4 bins</td>
</tr>
<tr>
<td>2000</td>
<td>af</td>
<td>29.3 bins</td>
<td>6.9 bins</td>
<td>24.0 %</td>
<td>56.0 %</td>
<td>33.3 %</td>
<td>2.3 bins</td>
</tr>
<tr>
<td></td>
<td>gr</td>
<td>34.7 bins</td>
<td>10.1 bins</td>
<td>29.1 %</td>
<td>58.6 %</td>
<td>37.0 %</td>
<td>3.7 bins</td>
</tr>
<tr>
<td>2001</td>
<td>af</td>
<td>38.8 bins</td>
<td>13.4 bins</td>
<td>34.5 %</td>
<td>73.0 %</td>
<td>54.3 %</td>
<td>7.3 bins</td>
</tr>
<tr>
<td></td>
<td>gr</td>
<td>37.3 bins</td>
<td>10.3 bins</td>
<td>27.6 %</td>
<td>60.0 %</td>
<td>49.3 %</td>
<td>5.1 bins</td>
</tr>
<tr>
<td>2002</td>
<td>af</td>
<td>40.2 bins</td>
<td>19.1 bins</td>
<td>47.5 %</td>
<td>30.0 %</td>
<td>17.0 %</td>
<td>3.2 bins</td>
</tr>
<tr>
<td></td>
<td>gr</td>
<td>25.7 bins</td>
<td>13.4 bins</td>
<td>52.1 %</td>
<td>31.0 %</td>
<td>18.0 %</td>
<td>2.4 bins</td>
</tr>
</tbody>
</table>
that in any given year leafrollers, managed conventionally, will account for 5-6 % of fruit cullage (L. Garcia, 2002). Thus it would appear that, without insecticides, leafroller damage for both treatments was not modest in year four for either treatment. It is also interesting that for the first three years, inclusive of the year when leafroller populations were extremely high, total percent cullage was not appreciably different between years. That is, even with the highest leafroller populations and associated elevated leafroller damage overall cullage rates did not increase commensurately. Could it be that fruits fed upon by leafrollers are somehow predisposed to other injuries that would otherwise result in their cullage? For year four then, based on the above estimation of exclusive leafroller fruit damage percentage of total cullage, alfalfa plots lost, on average, 1.64 bins per acre to leafroller damage exclusively (19.1 bins total cullage per plot x 8.6 %) and grass plots lost, on average 1.2 bins (13.4 bins total cullage per plot x 9.0 %). The average gross return for a bin of Fuji apples that year was $220.00. Approximately half of that, $110.00, constitutes net return/bin. The cost of conventional leafroller control in Washington apple orchards (a delayed dormant chlorpyriphos application and two Bt covers) is estimated to be approximately $155.00 per acre. Per the calculations above and based on average gross return, alfalfa plots lost approximately $132.00, net, worth of apples in 2002, a value approaching estimated cost of control. In year four approximately 50% or more (10 bins/acre) of all cullage was due to a disastrous codling moth outbreak and subsequent fruit injury. These apples were removed from the orchard prior to harvest but were still included the total cullage calculation. Had there not been a failure in codling moth control with the resulting crop reduction, economic threshold calculations for leafroller damage would indicate that the cost of leafroller control would exceed the value of damaged fruit. Total cullage from leafroller injury in alfalfa plots, as a percentage, would have been only 0.82 bins (19.1 bins x .5) per acre. Based on the gross value of $220/ bin (net return of $110), a net value of $90 for fruit damaged by leafrollers is well below the cost of control. Of course net loss exclusively from leafroller
damage was likely much greater the previous year when leafroller populations peaked and over the course of four years it is very likely that total fruit loss to leafroller damage would exceed cumulative cost of control.

The cullage analysis performed was simplistic. Field sorting at harvest, removing codling moth-injured fruit during the growing season, integrating packing shed cullage data, and the sheer size of the plots made cullage estimation and cause determination difficult. Nonetheless the trend of reduced leafroller damage by year four is apparent and the economic threshold was only approached. Additionally though, one should also account for the cumulative cost (in this case over four years) of achieving this level of biological control of leafrollers for a truer economic evaluation. That being the case, one should also question what other, less apparent costs, such as loss of biological control agents for leafrollers and other arthropods, environmental contamination, regulatory costs, worker safety and loss of consumer confidence and market share etc. are incurred when conventional control is utilized. Were these hidden costs accounted for would leafroller control using conventional methods remain to appear even marginally economical? The question also remains if leafroller populations and subsequently their damage to fruit and economic impact would continue to decline under the experimental conditions.

**Conclusion**

When parasitoid - leafroller population homeostasis can be achieved under the orchard management regime imposed in this experiment remains in question. The same could be said for other arthropod populations. Regardless, it may be that the low levels of *P. pyrusana* realized in year four of this study would not be problematic and could be kept in check by natural controls with either an alfalfa or grass cover. Continued monitoring in such an orchard environment would be required to make any such conclusion. Additionally, given the tremendous increase in
leafroller populations and subsequent fruit damage in proceeding years the affordability of achieving biological control in question. Further decline in the leafroller populations could also occur. However, several conclusions can be drawn from this study. Based on the population increase and decline trend observed, it may be that *P. pyrusana*, to some extent, is a pest whose population level may be substantially affected by the use or absence of broad-spectrum insecticides (Flint and van den Bosch, 1981) though this was not directly tested in this study. For both the experimental management regimes imposed there was at first a dramatic increase and then an equally dramatic decrease in population levels of *P. pyrusana* but only a modest to negligible gain in parasitoid activity (Bostanian et al., 2001; Brown and Adler, 1989; Brown and Welker, 1992). Populations rose quickly to nearly 100% shoot infestation levels in year three and then declined substantially in year four. The dramatic reduction in leafroller populations was largely attributed to a granulovirus epidemic though this is only hypothesized and was not conclusively determined. Parasitism by a complex of parasitoids also contributed to leafroller population control. Increased predation by generalists may also have contributed to the decline in leafroller populations but this too is based only on casual evidence and was not quantified. Parasitism lagged behind leafroller population increases by one year for both cover treatments. Alfalfa cover did not appreciably increase *P. pyrusana* parasitism rates or enhance biological control though there were more generalist predators in the alfalfa treatment. Predation by generalist predators, most notably spiders and earwigs, seemed to have increased though, again, this was not tested. The three parasitoids detected in both *P. pyrusana* and sentinel obliquebanded leafroller were, as anticipated, tachinids, Braconidae and *C. florus* (Beers et al., 1993). Tachinids were most prevalent in the early season and may have potential for further augmentation to provide overwintering generation biocontrol. Braconidae dominated the mid-season and *C. florus* did not exert significant control until fall supporting the understanding that it does not overwinter in the orchard or in association with orchard leafrollers. It seems
substantiated that, as anticipated, without augmentation *C. florus* is not predisposed to contribute to early season leafroller parasitism. There also seemed to be a sort of differential host preference exhibited by the various parasitoids. Braconidae proved to be the prevalent early season *P. pyrusana* parasitoid while tachinids predominated early season obliquebanded leafroller parasitism. Altogether Braconidae and *C. florus* were the dominant parasitoids of *P. pyrusana* with tachinids only occasionally detected. Conversely tachinids were an important component of the obliquebanded leafroller parasitoid complex each year of the experiment. It was interesting that the very high rate of late season tachinid parasitism of sentinel obliquebanded leafroller existed in year one and then all but disappeared in subsequent years. It may be that tachinids are more tolerant to commonly used insecticides and as the experiment progressed those parasitoids more sensitive became increasingly prevalent and displaced the tachinids.

There is only the most modest evidence that the use of alfalfa as an apple orchard cover crop promoted biological control of orchard leafrollers and ultimately contributed to lowering the pest’s population level. Whether the degree of biological control achievable from this factor alone would be sufficient to preclude economic injury is unclear.

Additionally, it must be noted that there were many non-significant, equivocal results as indicated by very low power of the test values. It may very well be that the tests were not strong enough to detect differences between cover crop treatments if they existed. This shortcoming arose from having only three treatment replicates. The larger, 0.5 ha plot sizes (instead of more, smaller plots) were a calculated compromise intended to mitigate potential small plot size effect on arthropod community population dynamics and to better approximate an agricultural environment.

It seems though, that elevated leafroller populations and the fruit damage they caused did not appreciably affect overall cullage rates. This is a point for further investigation. It is clear
however that leafroller parasitoid enhancement via conservation and habitat manipulation has
some potential as part of an integrated, biologically intensive management strategy. It is also
apparent that more hymenopterous species than anticipated comprise the leafroller parasitoid
complex. It is imperative to fully characterize the species attacking both *P. pyrusana* and
obliquebanded leafroller. Specific environmental manipulations may differentially enhance
various species and as such the overall efficacy of biologically based leafroller management by a
complex of natural enemies. Given the notion, as demonstrated in this study, that no single
parasitoid species will provide extensive biological control of leafrollers it seems that it will be
necessary to augment and or conserve the full extent of the parasitoid complex in the orchard
system to achieve and sustain biological control of apple leafrollers by natural enemies.
CHAPTER FOUR
CODLING MOTH, SECONDARY PEST AND NATURAL ENEMY POPULATIONS

Introduction

In the semi-arid Northwest, apple farmers, like their counterparts throughout the world have come to rely on broad-spectrum insecticides for insect pest management (Hull et al. 1983; Suckling et al. 1999; Weaver et al. 1990). Broad-spectrum insecticides are often lethal to competitors and/or biological control organisms (natural enemies) that have a role in keeping secondary arthropod pests in check (Pedigo, 2002). Additionally these pests often evolve resistance to pesticides faster than do beneficial predators and parasites (Tabasnik and Croft, 1985). Thus, when broad-spectrum pesticides are employed for management of primary pests, previously non-pest or secondary pest species become problematic as a result of the elimination or reduction in natural control agents (Beers 1998; Carl, 1996; Luna and House, 1990; National Research Council, 1996). Flint and van den Bosch (1981) note that the post-World War II pesticide revolution "ushered in a whole new spectrum of previously unknown pests". Many arthropods whose populations had been generally small or moderate became major crop pests. They attributed this to insecticide-induced mortality of natural enemies and pest tolerance to pesticides in conjunction with tremendous pest species reproductive capabilities. Several apple arthropod pests have reached seriously problematic levels, according to Croft (1982), because their natural enemies have been killed or adversely affected by pesticides. Examples of this include San Jose scale, oystershell scale, European red mite, two-spotted spider mite, apple rust mite, rosy apple aphid, wooly apple aphid, white apple leafhopper and red-banded leafroller. Entomologists generally observe and indicate that the loss of natural enemies due to insecticide use is severe in many parts of the world. This is serious, according to Pimental et al. (1992) in
that biocontrol by natural enemies in natural systems and agroecosystems may account for 50% to 90% of pest species control while pesticides provide an additional 10% control and other factors (e.g. host plant resistance, disease and other limiting factors) the remainder. The extensive use of fertilizers and pesticides probably has the greatest effects on species diversity and stability in orchard systems. Pesticides, depending on the extent of use, concentrations and selectivity may greatly reduce the number of arthropod species, favoring those with high dispersal and rapid re-colonization capabilities as well as those tolerant or resistant (Croft and Hull, 1983). Orchardists and orchard pest management investigators around the world have consistently noted changes in the arthropod community with the use or the absence of particular pesticides and pest management regimes (Altieri et al, 1993; Beers and Brunner, 1999; Beers et al. 1998; Brown, 1993; Brown and Scmitt, 2001; Brown and Adler, 1998; Gut et al. 1995; Jenser et al., 1999; Niemczyk, 1997; Polesney, 1996a; Polesney, 1996b; Prokopy et al. 1980; Suckling et al. 1999; Trimble and Vickers 2000; Walters, 1973).

Additionally agroecologists have long held that plant diversification, or lack thereof, can affect arthropod densities. Increased floral diversification has been demonstrated to reduce phytophagous arthropod incidence (Bugg and Pickett, 1998; Southwood and May, 1970). Many studies have shown that it is possible to stabilize insect communities in agroecosystems via the design and construction of “vegetational architectures” that support populations of natural enemies or have direct deterrent effects on pest herbivores. These studies suggest that the more diverse the agroecosystem and the longer it remains undisturbed (sans pesticides for example) the more internal links develop to promote greater insect stability (Altieri, 1994). Andow (1991) reviewed 209 published studies about vegetative biodiversity and arthropod herbivores in agricultural systems and determined that fifty-two percent (52%) of the 287 species studied were found to be less abundant in diversified systems. Only 15, or three percent (3%) exhibited higher
densities. Thus diversification of the flora in agroecosystems can contribute significantly to biologically-based pest management.

We have developed apple agroecosystems that create or exacerbate arthropod pest problems but ultimately biological and ecological processes are fundamental to pest management even in the most intensively managed agroecosystems (National Research Council, 1996). Sustained management of pests lies in ecologically and systems-based solutions. The advent of pheromone based mating disruption for the management of codling moth (*Cydia pomonella*) and the subsequent elimination of broad-spectrum insecticide applications for its control has resulted in an opportunity to substantively pursue study of ecologically-based pest management systems in Washington State apple orchards with potential to substantially reduce if not completely eliminate insecticide application.

To that end the objective of this study was to evaluate the effect of alfalfa and grass covers on selected species of the general arthropod community in an apple orchard managed without the use of insecticides during the growing season.

**Materials and Methods**

This study was conducted from the spring of 1999 through winter of 2002 and was inclusive of four growing seasons. Plots for this study were as described in the Materials and Methods section of Chapter Three.

The following procedures were utilized to assess insect and mite pests as well as some natural enemy populations during the course of the experiment:
Codling moth - Codling moth (*Cydia pomonella*) adults were monitored by delta traps (Treec Inc. Salinas, CA). Two per plot were put in at bloom or shortly thereafter. The traps were hung in the upper third of the tree canopy. Ten mg lures (Scenturion) were used in each trap. Lures were replaced every 3 weeks during the spring and every 2 weeks in summer. Traps were checked twice weekly and the number of moths recorded. Trap monitoring continued through September.

Codling moth injury to fruit- After first generation hatch, in late June or early July, the outer halves of 30 exposed fruits from each of 30 trees per plot were inspected for codling moth injury. The number of fruit with codling injury was recorded and the percent injury calculated by dividing the total injury in half and dividing it by the number of fruit sampled.

Aphids- Green apple aphid, *Aphis pomi*, De Geer and apple grain aphid, *Rhopalosiphum fitchii* (Sanderson) densities were assessed by inspecting 5 vigorous shoots in the upper canopy on each of 30 trees per plot. This inspection was repeated every three weeks throughout summer (early June through early August). The number of shoots with 5 or more infested leaves as well as the species was recorded. Rosy apple aphid, *Dysaphis plantaginea* Passerini, infestations were assessed in early June. Spurs and shoots, on 30 trees per plot, were examined for two minutes. The number of colonies per tree was noted. Additionally, the presence of common aphid predators (lacewings, ladybird beetles, syrphid flies) of all species was assessed.

Bugs and Thrips- Beginning at the full bloom stage of tree development (in early May) beating tray (limb tap) samples were taken in the experimental plots to assess densities of Mullein bug, *Campylomma verbasci* (Meyer); western flower thrips, *Frankliniella occidentalis* (Pergande), lygus bug, *Lygus lineolaris* (Palisot de Beauvois) and consperse and green stinkbugs, *Euschistus conspersus* Uhler and *Acrosternum hilare* (Say). Thirty beating tray samples, two trays per tree
on 15 randomly chosen sample trees (one black surface tray and one white surface tray for each tree), were taken in each plot at each sample. Per standard procedure (Beers et al., 1993) uniform branches were selected and subject to three vigorous taps each with the tray underneath to catch dislodged arthropods. Beating tray sampling was conducted weekly for three consecutive weeks. I recorded the number of mullein bug, western flower thrips, lygus bug, and stinkbug per tray per plot. Arthropods other than those previously listed were also noted.

White apple leafhopper, *Tyhlocyba pomaria* McAtee - In mid May and again in early August white apple leafhopper densities were assessed by inspecting the underside of 5 leaves from each of 30 trees per plot. The number of nymphs per leaf was recorded.

Western tentiform leafminer, *Phyllonorycter elmaella* Doglanar & Mutuura, - Starting in late May or early June, when western tentiform leafminer tissue feeders were first present and thereafter every three weeks through August, 5 mid-shoot leaves from each of 30 trees per plot (150 leaf samples) were collected. If mines were scarce, leaves with mines, for up to 30 minutes per plot to a maximum of 100 mines per plot, were collected. Collected leaves were brought to the lab where the mines were dissected and the % parasitism and parasitoid species was recorded.

Phytophagous and predatory mites- Populations of the phytophageous mites, McDaniel spider mite, *Tetranychus mcdanieli* McGregor, two-spotted spider mite, *Tetranychus urticae* Koch, European red mite, *Panonychus ulmi* (Koch) and the predaceous mites, *Typhlodromus occidentalis* (Nesbitt) and *Zetzalia mali* (Ewing) were assessed via the leaf collection and brushing technique. I collected 5 leaves from each of 10 trees per plot. The leaf samples were brought to the lab where each leaf was brushed. Active phytophagous and predatory mites were
This procedure was repeated every three weeks starting in early June and continuing through early September.

Overwintering arthropods- to assess overwintering diversity of the general arthropod population, I placed 2.5cm wide, corrugated cardboard strips around the base of 30 sample trees in each plot to serve as overwintering retreats. The strips were secured to trees at their crown in mid-August. The bands were then collected in mid-October, stored in plastic bags refrigerated (5.7° C) until January. The bands, still in plastic bags, were then removed from refrigeration, left at room temperature for 2 weeks or more and then examined for arthropods. Species present were identified and counted.

Results and Discussion

Adult codling moth, the key apple pest in Washington State, was assessed, throughout the growing season, by pheromone trapping. Mean weekly, first and second generation, trap catches generally increased during the study (Table 4.1). Trap catches in year four were substantially greater, for both treatments, than in previous years. There was no difference (either generation) in trap catches for either cover treatment in any year (power of the test = 0.28, 0.26 0.08, and 0.05 for the first generation in years one, two, three and four respectively and 0.11, 0.11, 0.09 and 0.38 for the second generation in years one, two, three and four respectively). The increase in codling moth populations, in years three and four, are attributable to a failure of codling moth mating disruption as a stand-alone management tool resulting in a severe pest outbreak and substantial fruit damage in year four (Figure 4.1). An estimated 10 bins (approximately 3900 kg) per plot was destroyed. This constituted as much as one-quarter of the crop. Codling moth damage to fruits was assessed, after first generation egg hatch, by examining fruits for larval feeding and entrance holes. Results reflect the buildup and outbreak, which occurred in year
Table 4.1. Mean weekly, first and second generation, adult codling moth males caught in sticky wing traps hung in the tree canopy. male

<table>
<thead>
<tr>
<th>Year</th>
<th>alfalfa</th>
<th>S.D.</th>
<th>grass</th>
<th>S.D.</th>
<th>alfalfa</th>
<th>S.D.</th>
<th>grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.28a</td>
<td>0.14</td>
<td>0.19a</td>
<td>0.21</td>
<td>0.36a</td>
<td>0.17</td>
<td>0.22a</td>
<td>0.25</td>
</tr>
<tr>
<td>2000</td>
<td>0.00a</td>
<td>0.00</td>
<td>0.13a</td>
<td>0.11</td>
<td>0.50a</td>
<td>0.25</td>
<td>0.16a</td>
<td>0.28</td>
</tr>
<tr>
<td>2001</td>
<td>0.54a</td>
<td>0.38</td>
<td>0.33a</td>
<td>0.35</td>
<td>1.21a</td>
<td>0.58</td>
<td>1.07a</td>
<td>0.33</td>
</tr>
<tr>
<td>2002</td>
<td>5.20a</td>
<td>2.87</td>
<td>3.96a</td>
<td>0.05</td>
<td>9.90a</td>
<td>7.01</td>
<td>5.26a</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). Each generation was analyzed separately. Treatments were compared for each year separately.

Figure 4.1. Mean weekly, first and second generation, adult codling moth males caught in sticky wing traps hung in the tree canopy.
four. Injury to fruits was greatest in year four for both cover treatments. In years one (F= 206.15, DF= 1,4; P< 0.001), three (F= 34597.12; DF= 1,4; P< 0.001) and four (F= 52.20, DF= 1,4: P= 0.001) grass treatment plot first generation codling moth fruit injury was significantly greater than for alfalfa treatment plots (Table 4.2). In year two there was no injury detected.

It was the first time such a failure had occurred in this orchard since its establishment in 1992. The outbreak is attributable to several factors. First, a half rate (200 Isomate C-plus dispensers per acre) of pheromone treatment was applied as it had traditionally been. Secondly, pheromone emitter placement was not optimum; many were inadvertently placed too low (midway) in the canopy as opposed to the top of the canopy as recommended. External pressure in recent years had also increased substantially in the surrounding area because depressed economic conditions from low fruit returns resulted in area orchards not being managed for codling moth as intensively or aggressively as previously. Likewise many orchards were abandoned or pulled out and left without adequate codling moth management. Additionally a nearby apple packing facility began stockpiling large quantities of storage bins very nearby during the course of the study. Diapausing codling moths are known to infest bins and as the bins are emptied during packing they are stored in outside stacks. Codling moths emerge from their hibernacula, that are in protected portions in these stacked bins, all season long. They mate and females seek apple trees to oviposit on. The experimental plots were located downwind from both abandoned/neglected orchards and the bin piles. Frequently strong and fairly constant prevailing winds likely assisted the migration of moths from neglected orchards and bins stacks to the test plots. It is most likely, if not certain, that internal codling moth populations built up over the years of the study (as well as preceding years) as a result of these external pressures and subsequent immigration of mated female moths (J. Brunner, 2002). It is therefore supported that
Table 4.2. Mean percentage rate of fruit injury from codling moth larvae after 1st generation egg hatch in alfalfa and grass cover plots.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>1.00 b</td>
<td>0.10</td>
<td>2.00 a</td>
<td>0.14</td>
</tr>
<tr>
<td>2000</td>
<td>0.00 a</td>
<td>0.00</td>
<td>0.00 a</td>
<td>0.00</td>
</tr>
<tr>
<td>2001</td>
<td>1.00 b</td>
<td>0.10</td>
<td>3.00 a</td>
<td>0.18</td>
</tr>
<tr>
<td>2002</td>
<td>8.00 b</td>
<td>0.26</td>
<td>10.00 a</td>
<td>0.30</td>
</tr>
</tbody>
</table>

Means were transformed for analysis, those followed by the same letter are not significantly different ($P = 0.05$). See F values cited in the text. Treatments were compared for each year separately.
this exotic pest is subject to few natural control mechanisms in the orchard environment. As such, intermittent therapeutic control measures to supplement and support mating disruption are necessary (Brunner et al., 1994). Such measures must be chosen and integrated into the system so as not to harm natural enemies of secondary pests and disrupt the biological control of the latter.

Limb tap samples were conducted in spring (starting at full bloom and for three consecutive weeks thereafter) to assess populations of mullein bug, lygus bug, western flower thrips and stink bug (Table 4.3). Mullein bug populations were highest, for both alfalfa and grass treatments, in year two of the study (Figure 4.2). In year four mullein bug populations in the alfalfa plots were not appreciably greater than year one populations and in no year were populations significantly greater in either cover treatment (power of the test = 0.05, 0.25, 0.51 and 0.06 for years one, two, three and four respectively). At no time did populations produce any level of fruit damage. Mullein bug populations are noted to vary from season to season in conventionally managed orchards and as such the variation in population levels in experimental plots did not represent anything unusual or unacceptable. In addition to feeding on fruitlets in the spring, mullein plant bugs are also predators of soft-bodied insects so it may well be that elevated populations were of benefit (Beers et al., 1993).

Lygus bug is of particular concern with the use of alfalfa as an orchard cover. Alfalfa is a preferred host plant of this insect and can support large populations that are reputed to have potential to move into apple trees, particularly after alfalfa mowing (Beers et al., 1993). Lygus bug beating tray counts were, overall, highest in alfalfa plots. In fact, for alfalfa plots lygus bug populations increased in each successive year of the experiment (Figure 4.2). In year four, alfalfa plot lygus bug beating tray counts were significantly higher (F = 4.77; DF = 1,22; P =
0.039) than for the grass treatments (Table 4.3). In previous years there was no difference between cover treatments (power of the test = data all zeros, 0.05, 0.14 and 0.97 for years one, two and three respectively). Despite increasing higher lygus bug populations in the alfalfa treatment plots no discernable fruit injury was observed. While the alfalfa cover encouraged increased lygus bug populations, it seems they did not migrate from the alfalfa cover to the tree canopy in numbers sufficient to result in discernable fruit injury. Alternate row mowing, separated by a week or more, may have discouraged lygus bug movement from the alfalfa cover to tree canopies.

Populations of western flower thrips vacillated greatly between cover crop treatments and between years throughout the study (Figure 4.2). The highest levels, for grass and alfalfa treatments, occurred in year one, the first year of the study and in the final year (four). Alfalfa treatment populations were significantly greater than grass in year one (F = 28.32; DF=1,16; P<0.001). In subsequent years there was no difference between cover treatments (power of the test = 0.71, 0.35 and 0.19 for years two, three and four respectively). The lowest levels for both grass and alfalfa cover treatments were in year two. There was no practical difference in western flower thrips densities between cover crop treatments in any year over the course of the study (Table 4.3).

Stinkbugs were all but absent in the spring in both cover crop treatments in all years of the study (Table 4.3; Figure 4.2). In no year were populations significantly greater in either cover crop treatment (power of the test = data all zeros for years one and two and 0.05 for both years three and four). It was noted that, in addition to the above species, spiders were frequently observed in limb tap samples. Though I did not quantify it, their detection in limb tap samples seemed to increase substantially as the study progressed. Earwigs were also detected in limb tap samples in the last year of the study.
Table 4.3. Mean number of mullein plant bugs, lygus bugs, stink bugs and thrips counted on bloom time limb tap samples in alfalfa and grass cover plots.

<table>
<thead>
<tr>
<th>Year</th>
<th>Mullein Bug</th>
<th>Lygus</th>
<th>Stink Bug</th>
<th>Thrips</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.89 a</td>
<td>0.66</td>
<td>0.44 a</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>57.56 a</td>
<td>11.57</td>
<td>32.88 b</td>
<td>7.15</td>
</tr>
<tr>
<td>2000</td>
<td>4.17 a</td>
<td>3.40</td>
<td>2.30 a</td>
<td>1.91</td>
</tr>
<tr>
<td></td>
<td>13.08 a</td>
<td>15.51</td>
<td>20.25 a</td>
<td>25.50</td>
</tr>
<tr>
<td>2001</td>
<td>0.42 a</td>
<td>0.86</td>
<td>0.67 a</td>
<td>1.31</td>
</tr>
<tr>
<td></td>
<td>28.92 a</td>
<td>30.12</td>
<td>32.58 a</td>
<td>33.00</td>
</tr>
<tr>
<td>2002</td>
<td>1.75 a</td>
<td>0.66</td>
<td>1.42 a</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>47.83 a</td>
<td>41.68</td>
<td>45.67 a</td>
<td>35.02</td>
</tr>
</tbody>
</table>

Means followed by the same letter not significantly different (P = 0.05). See F values cited in the text. Treatments were compared for each year separately. Each species was analyzed separately.
Figure 4.2. Mean number of mullein plant bugs, lygus bugs, stink bugs and thrips counted on bloom time limb tap samples in alfalfa and grass cover plots.
White apple leafhopper nymph densities were assessed in mid-May and early August. Data were combined between the two sampling times for analysis (Figure 4.3). The number of nymphs per leaf was greatest in year two for both cover treatments, 1.1 for alfalfa and 1.0 for grass, but they were not different from each other (power of the test = 0.05). Only in year one were alfalfa plot populations significantly greater than grass plots populations (F= 8.05; DF= 1,358; P= 0.004). Otherwise, for other years and both cover treatments, densities ranged from 0.3 to 0.68 nymphs per leaf (Table 4.4) and were not significantly different from one another (power of the test = 0.10 and 0.66 for years three and four respectively). In no year, for either treatment, were white apple leafhopper populations problematic.

Western tentiform leafminer densities were evaluated by collecting leaves and examining mines for tissue-feeding larvae. Rates of parasitism were also assessed. Beginning in late May or early June through August, every three weeks, leaves were collected. Third generation tissue feeding leafminer populations are considered most indicative of population and parasitism. Thus third generation data were utilized for analysis of population levels between treatments (Table 4.5). The greatest number of mines per leaf occurred in year two (Figure 4.4). Alfalfa treatment plots averaged 0.09 mines per leaf while grass had an average 0.10 mines per leaf. For both cover treatments in the last two years no western tentiform leafminers were found. In years one and two were infestation levels were not significantly greater for one treatment or the other (power of the test = 0.85 and 0.11 for years one and two respectively). Seasonal parasitism by *Ponzalio flavipes* (exclusively) was much greater in year two (alfalfa- 68.53%, grass 69.71%) for both cover treatments than in year one (alfalfa- 30.89%, grass- 20.68%). At no time, for either cover treatment, did populations of western tentiform leafminer, even with the lower parasitism rates, reach problematic levels.
Table 4.4. Mean number of white apple leafhopper nymphs, per leaf, on alfalfa and grass cover crop plot trees for spring and summer sampling periods combined, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.68 a</td>
<td>1.03</td>
<td>0.42 b</td>
<td>0.71</td>
</tr>
<tr>
<td>2000</td>
<td>1.10 a</td>
<td>2.87</td>
<td>1.01 a</td>
<td>3.03</td>
</tr>
<tr>
<td>2001</td>
<td>0.30 a</td>
<td>0.76</td>
<td>0.34 a</td>
<td>0.80</td>
</tr>
<tr>
<td>2002</td>
<td>0.63 a</td>
<td>1.15</td>
<td>0.53 a</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Means followed by the same letter not significantly different ($P = 0.05$). See F values cited in the text. Treatments were compared for each year separately.

Figure 4.3. Mean number of white apple leafhopper nymphs, per leaf, on alfalfa and grass cover crop plot trees for spring and summer sampling periods combined, by year.
Table 4.5. Mean number of 3rd generation western tentiform leafminer tissue feeders per leaf for alfalfa and grass cover plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.09a</td>
<td>1.59</td>
<td>0.10a</td>
<td>1.82</td>
</tr>
<tr>
<td>2000</td>
<td>0.53a</td>
<td>4.3</td>
<td>0.60a</td>
<td>4.55</td>
</tr>
<tr>
<td>2001</td>
<td>0.00a</td>
<td>0.00</td>
<td>0.00a</td>
<td>0.00</td>
</tr>
<tr>
<td>2002</td>
<td>0.00a</td>
<td>0.00</td>
<td>0.00a</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). Treatments were compared for each year separately.

Figure 4.4. Mean number of 3rd generation western tentiform leafminer tissue feeders per leaf for alfalfa and grass cover plots, by year.
No apple grain or green apple aphids were detected in the final year (four) of the study but the previous year (three) had the highest number of colonized shoots (Figure 4.5). Alfalfa treatment plots, in year three, averaged 23.93 colonized shoots per plot while grass plots had 13.93 colonized shoots (Table 4.6). However, third year shoot infestation levels were not such that control would be warranted (Beers et al., 1993). In no year were alfalfa plot infestation levels significantly different from grass plot levels (power of the test = 0.07, 0.39, and 0.05 for years one, two and three respectively).

Rosy apple aphid infestations were greatest the final year of the study, 9.56 colonies per plot for grass and 7.89 colonies per plot for alfalfa (Figure 4.6). These levels did not differ statistically (power of the test = 0.10) from one another (Table 4.7) nor did they for other years (power of the test = 0.06, 0.22 and 0.10 for years one, two, and three respectively). Shoot colonization levels were nil the year previous for both grass and alfalfa cover treatments. At no time during the study did rosy apple aphid populations exceed recommended treatment thresholds (Beers et al., 1993). All colonies of apple grain aphid, green apple aphid and rosy apple aphid disappeared as the summer progressed and at no time did they reach population levels requiring treatment. The trees in experimental plots were mature and able to tolerate the aphid infestations noted above. Orchardists are less tolerant of aphid infestation in young trees. Infestation levels of green apple/apple grain aphid such as those observed in 2001 may have been detrimental to newly established trees. Likewise the rosy apple aphid infestation levels observed in year four may have been cause for concern on establishing trees.

Many aphid predators, which surely contributed to their control, were also observed in the colonies. They were counted for the last three years of the study. Aphid predators observed include ladybird beetles and their larvae, *Hippodamia convergens* Guein-Meneville or
Table 4.6. Seasonal mean number of tree shoots colonized by apple grain aphid and/or green apple aphid in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>2.40a</td>
<td>3.54</td>
<td>1.40a</td>
<td>1.95</td>
</tr>
<tr>
<td>2000</td>
<td>1.67a</td>
<td>2.87</td>
<td>1.27a</td>
<td>2.28</td>
</tr>
<tr>
<td>2001</td>
<td>23.93a</td>
<td>31.03</td>
<td>13.93a</td>
<td>18.34</td>
</tr>
<tr>
<td>2002</td>
<td>0.00a</td>
<td>0.00</td>
<td>0.00a</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). Treatments were compared for each year separately.

Figure 4.5. Seasonal mean number of tree shoots colonized by apple grain aphid and/or green apple aphid in alfalfa and grass cover crop plots, by year.
Table 4.7. Seasonal mean number of apple tree shoots colonized by rosy apple aphid in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.50 a</td>
<td>1.22</td>
<td>1.17 a</td>
<td>2.85</td>
</tr>
<tr>
<td>2000</td>
<td>1.00 a</td>
<td>0.63</td>
<td>0.33 a</td>
<td>0.51</td>
</tr>
<tr>
<td>2001</td>
<td>0.00 a</td>
<td>0.00</td>
<td>0.00 a</td>
<td>0.00</td>
</tr>
<tr>
<td>2002</td>
<td>7.89 a</td>
<td>7.91</td>
<td>9.56 a</td>
<td>9.54</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). Treatments were compared for each year separately.

Figure 4.6. Seasonal mean number of apple tree shoots colonized by rosy apple aphid in alfalfa and grass cover crop plots, by year.
**Coccinella transversoguttata richardsoni** Brown; green lacewing adults and larvae, *Chrysoperla carnea* (Stephens) or *C. nigricornis* Burmeister; *Deraeocoris brevis piceatus* (Knight); damsel bug, *Nabis* spp.; syrphid fly larvae, *Scaeva pyrastris* (Linneaus) or *Eupeodes volucris* Osten Sacken; predaceous midge, minute pirate bug and spiders (Araneae). Ladybird beetles and their larvae were observed most frequently and in the greatest quantities. Their presence, both immature and adult stages, was greatest the last year of the study (Figure 4.7). In year three adult ladybird beetle were present in significantly greater numbers in alfalfa plots than in grass plots ($F= 8.04$, $DF= 1, 28$, $P= 0.008$). Otherwise there was no difference in ladybird beetle larvae (power of the test = 0.21, 0.93 and 0.99 for years two, three and four respectively) or adult (power of the test = 0.19, 0.46 and 0.83 for years two, three and four respectively) infestation levels between grass and alfalfa cover crop plots in any year of the study (Table 4.8). Green lacewing adults and larvae were also found, relatively frequently, preying on aphid colonies. Larvae were only observed in the last two of three years while adults were observed in all three years. There was no practical difference between cover crop treatments in any year. Lacewing eggs were frequently observed the last two years as well. For all three years *Deraeocoris* and damsel bugs were present only in small numbers, if at all, and there was no practical difference between cover crop treatments in any year. Likewise spiders were observed in association with aphid numbers that did not differ between cover crop treatments between years. They were observed in year three and year four only; none were present in year two. Syrphid fly and minute pirate bug were noted only in years three and four. They were present in very low numbers. Finally predaceous midges were relatively abundant in the final year (four) of the study after only a very few were observed the year before and none before that. It appears that generalist predator populations increased in both cover treatments, in the absence of broad-spectrum insecticides, during the course of this study. Though there were most often no
Table 4.8. Adult and immature ladybird beetles observed on aphid infested apple tree shoots in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Adults</th>
<th></th>
<th></th>
<th>Larvae</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alfalfa</td>
<td>S.D.</td>
<td>Grass</td>
<td>Alfalfa</td>
<td>S.D.</td>
<td>Grass</td>
</tr>
<tr>
<td>2000</td>
<td>1.00 a</td>
<td>1.00</td>
<td>0.00 a</td>
<td>0.00</td>
<td>3.00 a</td>
<td>3.60</td>
</tr>
<tr>
<td>2001</td>
<td>2.33 a</td>
<td>2.42</td>
<td>0.47 b</td>
<td>0.83</td>
<td>1.13 a</td>
<td>1.88</td>
</tr>
<tr>
<td>2002</td>
<td>6.12 a</td>
<td>4.16</td>
<td>5.58 a</td>
<td>3.23</td>
<td>15.33 a</td>
<td>13.03</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). See F values cited in the text. Treatments were compared for each year separately. Adults and larvae were analyzed separately.

Figure 4.7. Adult and immature ladybird beetles observed on aphid infested apple tree shoots in alfalfa and grass cover crop plots, by year.
significant differences in generalist predator populations between cover treatments measured
(with the exception of ladybird beetle and lacewing), it is interesting to note that all species,
except *DERAEOCORIS*, were more prevalent in alfalfa-covered plots in the final year.

Phytophagous and predatory mites were also monitored (Table 4.9). European red mite,
McDaniel spider mite, twospotted spider mite and apple rust mite populations all declined over
the course of the study in both cover treatments (Figure 4.8). In no year of the study there was
there a significant difference in population levels of any of these phytophagous mites between
cover crop treatments and at no time during the study were mite populations problematic (for
European red mite power of the test = 0.07, 0.05, 0.99 and 0.05 for years one, two, three and four
respectively; for McDaniel spider power of the test = 0.06, 0.97, 0.97 and 0.56 for years one,
two, three and four respectively; for two-spotted spider mite power of the test = 0.32, 0.05, 0.28
and 0.24 for years one, two, three and four respectively and for apple rust mite power of the test
= 0.05, 0.06, for years one, two respectively and for years three and four the data was all zeros).
Generally populations of apple rust mite and European red mite were quite low and by year four
few European red mites and no apple rust mites were detected. Twospotted and McDaniel mites
were originally present in much greater numbers but by year four populations were greatly
reduced. Predator mite, *ZETZELIJA MALI* (Ewing) and *GALADROMUS OCCIDENTALIS* Koch, populations
were also greatest in the first year of the study (Figure 4.9). Their numbers declined as their prey
populations declined so that after year one they were also very few in number. For both *Z. mali*
and *G. occidentalis* in year one there was no population level difference (power of the test = 0.99
and 0.99 respectively) between alfalfa and grass covers and populations in both covers were
greater than in subsequent years. There were no differences (For *Z. mali* data all zeros for years
two and three and power of the test = 0.84 for year four and for *G. occidentalis* power of the test

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Table 4.9. Mean phytophagous mite populations per sampling for alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Twospotted mite</th>
<th>McDaniel mite</th>
<th>European red mite</th>
<th>Apple rust mite</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>147.78 a</td>
<td>373.36</td>
<td>231.39 a</td>
<td>440.71</td>
</tr>
<tr>
<td>2000</td>
<td>0.08 a</td>
<td>0.28</td>
<td>0.00 a</td>
<td>0.00</td>
</tr>
<tr>
<td>2001</td>
<td>1.00 a</td>
<td>1.96</td>
<td>1.20 a</td>
<td>1.14</td>
</tr>
<tr>
<td>2002</td>
<td>3.00 a</td>
<td>3.68</td>
<td>4.00 a</td>
<td>3.87</td>
</tr>
</tbody>
</table>

Mean followed by the same letter are not significantly different ($P = 0.05$). See F values cited in the text. Treatments were compared for each year separately. Each species analyzed separately.
Figure 4.8 Mean phytophagous mite populations, for alfalfa or grass cover crop plots per sampling, by year.
= 0.67, 0.27 and 0.99 for years two, three and four respectively) in populations of predatory mites between cover treatments for the last three years of the study (Table 4.10).

Overwintering arthropod populations were assessed. Specimens collected were categorized as pest species, beneficial species or miscellaneous. Insect species trapped varied from year to year (Table 4.11). Overwintering beneficial insects trapped during the four years included, Hemerobiidae, Chalcidoidae, Syrphidae, Stethorus sp., Deraeocoris sp., Nabis spp., Apanteles sp., earwigs and green lacewings. Pests trapped over the four years included Arctiidae, Noctuidae, Lygus, winged aphids, leafhoppers, codling moth and leafrollers.

The fewest beneficials were collected from grass treatments in year one. Alfalfa treatments had significantly greater numbers of beneficial species than did grass treatments that year (F= 16.28; DF= 1,4; P= 0.015). For the other years there was no difference (power of the test = 0.18, 0.05 and 0.06 for years two, three and four respectively). The single largest collection of beneficial arthropods, was from alfalfa in year two. Generally the numbers collected, regardless of cover treatment, were quite small. Interestingly, the most diverse collection was that from year one.

The year three collection included only lacewings, Deraeocoris and damsel bugs. The year four collection included only Braconidae and earwigs. It was the first collection of earwigs. Indicated by this means of assessment it would not seem that either cover was particularly more conducive than the other to a general population of beneficial arthropods. However, it is noteworthy that for three of the four years, the alfalfa cover had the most overwintering beneficials (Table 4.12).

The greatest number of overwintering pest species was collected in year four for both treatments (Table 4.13). In no year was there a significantly greater overwintering pest species trap catch for either cover treatment (power of the test = 0.08, 0.05, 0.05 and 0.05 for years one, two, three
Table 4.10. Mean predatory mite populations, for alfalfa or grass cover crop plots per sampling, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th><em>Galadromus occidentalis</em></th>
<th></th>
<th><em>Zetzellia mali</em></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Alfalfa</td>
<td>S.D.</td>
<td>Grass S.D.</td>
<td>Alfalfa</td>
</tr>
<tr>
<td>1999</td>
<td>257.17 a</td>
<td>420.97</td>
<td>178.89 a</td>
<td>293.98</td>
</tr>
<tr>
<td>2000</td>
<td>1.00 a</td>
<td>1.70</td>
<td>1.25 a</td>
<td>2.13</td>
</tr>
<tr>
<td>2001</td>
<td>11.80 a</td>
<td>16.36</td>
<td>15.33 a</td>
<td>16.99</td>
</tr>
<tr>
<td>2002</td>
<td>13.67 a</td>
<td>10.60</td>
<td>17.33 a</td>
<td>12.08</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). Treatments were compared for each year separately. Each species was analyzed separately.
Figure 4.9. Mean predatory mite populations, from alfalfa or grass cover plots per sampling, by year.

- Alfalfa Galadromus occidentalis
- Grass Galadromus occidentalis
- Alfalfa Zettellia mali
- Grass Zettellia mali
Table 4.11. Number of individual arthropods classified as either beneficial or pest species, trapped in their overwintering stage in cardboard bands in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Codling moth</td>
<td>31</td>
<td>4</td>
<td>11</td>
<td>11</td>
<td>6</td>
<td>7</td>
<td>228</td>
<td>231</td>
</tr>
<tr>
<td>Leafroller</td>
<td>2</td>
<td>1</td>
<td>87</td>
<td>118</td>
<td>35</td>
<td>39</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Lygus</td>
<td>0</td>
<td>0</td>
<td>12</td>
<td>11</td>
<td>9</td>
<td>9</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lygaeidae</td>
<td>7</td>
<td>4</td>
<td>0</td>
<td>0</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Winged aphid</td>
<td>0</td>
<td>2</td>
<td>6</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Total pests</td>
<td>40</td>
<td>12</td>
<td>116</td>
<td>149</td>
<td>55</td>
<td>58</td>
<td>237</td>
<td>236</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Braconidae</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>9</td>
<td>12</td>
</tr>
<tr>
<td>Aphididae</td>
<td>6</td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hemerobidae</td>
<td>5</td>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Chalchidoidea</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Lacewing</td>
<td>0</td>
<td>1</td>
<td>26</td>
<td>23</td>
<td>17</td>
<td>10</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Stethorus</td>
<td>1</td>
<td>0</td>
<td>7</td>
<td>9</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Deraeocoris sp.</td>
<td>1</td>
<td>0</td>
<td>14</td>
<td>22</td>
<td>23</td>
<td>16</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Earwigs</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>16</td>
<td>15</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Araneae</td>
<td>1</td>
<td>0</td>
<td>37</td>
<td>15</td>
<td>15</td>
<td>20</td>
<td>6</td>
<td>10</td>
</tr>
<tr>
<td>Total beneficials</td>
<td>24</td>
<td>8</td>
<td>84</td>
<td>69</td>
<td>71</td>
<td>61</td>
<td>52</td>
<td>55</td>
</tr>
</tbody>
</table>
Table 4.12. Mean number of overwintering arthropods classified as beneficial species caught in cardboard band traps in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>20.33 a</td>
<td>6.02</td>
<td>5.00 b</td>
<td>2.64</td>
</tr>
<tr>
<td>2000</td>
<td>38.33 a</td>
<td>13.01</td>
<td>17.33 a</td>
<td>4.16</td>
</tr>
<tr>
<td>2001</td>
<td>18.67 a</td>
<td>7.50</td>
<td>18.67 a</td>
<td>1.15</td>
</tr>
<tr>
<td>2002</td>
<td>15.33 a</td>
<td>3.05</td>
<td>15.33 a</td>
<td>7.02</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). See F values cited in the text. Treatments were compared for each year separately.
Table 4.13. Mean number of arthropods, classified as pest species, caught overwintering in cardboard band traps in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>14.00 a</td>
<td>8.18</td>
<td>4.00 a</td>
<td>5.19</td>
</tr>
<tr>
<td>2000</td>
<td>38.33 a</td>
<td>13.03</td>
<td>50.33 a</td>
<td>26.55</td>
</tr>
<tr>
<td>2001</td>
<td>18.33 a</td>
<td>5.50</td>
<td>19.33 a</td>
<td>10.06</td>
</tr>
<tr>
<td>2002</td>
<td>78.33 a</td>
<td>93.02</td>
<td>78.66 a</td>
<td>60.05</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different ($P = 0.05$). Treatments were compared for each year separately.
and four respectively). The substantial increase in year four was overwhelmingly due to codling moth, which coincided with their outbreak in the previous growing season. In year one no codling moth or leafroller were collected. Had the outbreak of codling moth in year four been avoided and as such overwintering codling moth capture in year four resembled that of year one, then overall pest species captured in overwintering traps would have declined, indicating a general decrease in populations of pest species.

The greatest numbers of overwintering leafrollers were detected in year two (Table 4.14). An average of 39.33 overwintering leafroller were collected from grass plots and 29.00 from alfalfa plots in that year. They did not differ statistically from one another in that year ($\beta = 0.05$). This sharp increase in overwintering leafroller, from the year before may have been, in retrospect, indicative of the huge leafroller population to come in the year three growing season. Thus overwintering trap catch may be a valuable predictive tool. Overwintering leafroller trap catch declined greatly in year three to 13.0 in grass plots and 11.67 in alfalfa plots, then to 2.0 in alfalfa plots and 1.33 in grass plots in the final year (four) of the study. Overwintering leafrollers for either grass or alfalfa covers in years one, three and four were not different from one another (data all zeros for year one and power of the test = 0.06 and 0.05 for years three and four respectively). The fact that year four overwintering leafroller counts were so low (approaching the nil levels of year one) further supports the notion that the leafroller populations in all plots of the test block declined dramatically during the year four growing-season. In both years two and three overwintering leafroller trap catch was greatest in the grass treatment.

**Cullage analysis**

Cullage analysis was conducted for harvested fruit (Table 4.15). Field sorting of damaged fruit during harvest was a routine procedure so many fruits were culled in the field, others were culled
Table 4.14. Mean number of overwintering leafrollers caught in cardboard band traps in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>S.D.</th>
<th>Grass</th>
<th>S.D.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.00a</td>
<td>0.00</td>
<td>0.00a</td>
<td>0.00</td>
</tr>
<tr>
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<td>29.00a</td>
<td>12.12</td>
<td>39.33a</td>
<td>27.42</td>
</tr>
<tr>
<td>2001</td>
<td>11.67a</td>
<td>3.51</td>
<td>13.00a</td>
<td>11.00</td>
</tr>
<tr>
<td>2002</td>
<td>2.00a</td>
<td>1.0</td>
<td>1.33a</td>
<td>0.57</td>
</tr>
</tbody>
</table>

Means followed by the same letter are not significantly different (P = 0.05). Treatments were compared for each year separately.
during packing. Field culled fruit was estimated for each plot and combined with packing shed cullage for a total cullage estimates. Cull analysis indicated a general increase in codling moth injury over the course of the study. It is important to note that fruit injured by codling moth was removed from trees long before harvest as a routine management practice. In year four, codling moth injury was extensive for both treatments due to the failure of mating disruption in the face of enormous pressure and an estimated 7-8 bins per acre were destroyed by codling moth. The majority of arthropod pest injury in year four was from codling moth. The data reported (Table 4.15) does not reflect the extent of the damage because of pre-harvest, infested fruit removal. Leafroller damage was reported in the previous chapter. Cutworm damage fluctuated throughout the study and remained low. Stinkbug fruit injury was similar for both treatments throughout the study and quite high in years one and two due largely to late season immigration from dried out fields adjacent to the orchard. Stinkbug injury is not uncommon but occurs sporadically in Washington orchards. Aphid, scale and thrips injury was not apparent or was negligible for both treatments in all years. Finally lygus bug injury occurred for both treatments in years three and four only. There was no difference in injury levels for any treatment in any year.

Conclusion

In the absence of insecticide treatments, with the exception of codling moth and possibly leafroller, none of the arthropod species generally considered potential pests of apple caused economic damage to the fruit. This suggests (and in some instances confirms) that many insect and mite species are primarily pesticide-induced pests of apple and biological controls, if not disrupted, are sufficient to maintain pest populations below damaging levels (Flint and van den Bosch, 1981). Alfalfa, as a cover crop, seemed to have at best, only a slight effect on the
Table 4.15. Estimated percent of cullage with arthropod pest injury in alfalfa and grass cover crop plots, by year. *

<table>
<thead>
<tr>
<th>species</th>
<th>Alfalfa</th>
<th></th>
<th></th>
<th></th>
<th>Grass</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>codling moth</td>
<td>1.0 %</td>
<td>0.0 %</td>
<td>4.7 %</td>
<td>9.0 %</td>
<td>1.0 %</td>
<td>0.0 %</td>
<td>7.0 %</td>
<td>11.0 %</td>
</tr>
<tr>
<td>leafroller</td>
<td>12.0 %</td>
<td>33.0 %</td>
<td>17.0 %</td>
<td>7.0 %</td>
<td>15.0 %</td>
<td>37.0 %</td>
<td>15.3 %</td>
<td>7.6 %</td>
</tr>
<tr>
<td>aphid</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>cutworm</td>
<td>1.0 %</td>
<td>9.0 %</td>
<td>3.0 %</td>
<td>1.0 %</td>
<td>3.0 %</td>
<td>11.0 %</td>
<td>0.0 %</td>
<td>1.3 %</td>
</tr>
<tr>
<td>lygus bug</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>2.0 %</td>
<td>2.3 %</td>
<td>2.0 %</td>
<td>0.0 %</td>
<td>3.0 %</td>
<td>1.3 %</td>
</tr>
<tr>
<td>stinkbug</td>
<td>23.0 %</td>
<td>14.0 %</td>
<td>2.0 %</td>
<td>1.0 %</td>
<td>12.0 %</td>
<td>10.0 %</td>
<td>1.0 %</td>
<td>0.6 %</td>
</tr>
<tr>
<td>scale</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>1.3 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
<tr>
<td>thrips</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
<td>0.0 %</td>
</tr>
</tbody>
</table>

* Estimates based on damage on harvested fruit in bins. Field sorting of culls during harvest had been performed. Cause of cullage not necessarily exclusively from pest injury or injury from a single pest.
decrease of pest species or increase in beneficial species. It is apparent that insecticides are the preponderant mitigating factor relative to secondary pest incidence.

It must be noted, however, that there were many non-significant, equivocal results as indicated by very low power of the test values. It may very well be that the tests were not strong enough to detect differences between cover crop treatments if they existed. This shortcoming arose from having only three treatment replicates. The larger, 0.5 ha plot sizes (instead of more, smaller plots) were a calculated compromise intended to mitigate, to some extent, potential small plot size effect on arthropod community population dynamics and to better approximate an agricultural environment.

Codling moth populations (an exotic species with few natural enemies) did become excessive by year four, causing significant and unacceptable economic injury. This was due to extreme, continued, external pressure and subsequent failure of mating disruption as a stand-alone management tool. Substantially more aggressive management is called for including, likely, the last resort back-up use of insecticides as suggested by Lewis et al. (1997). The challenge will be to evoke an integrated management strategy for codling moth that will not disrupt the biological control of the myriad of secondary pest species that otherwise are not particularly problematic in the absence of pesticides. Materials exist that could be utilized in such a system and provide levels of leafroller management. I however choose not to use them in an effort to conserve leafrollers. Continued evaluation of materials for the management of codling moth that would not disrupt the biological control of secondary arthropods, as well as leafroller, is warranted.

Leafroller densities did increase in year three to cause substantial concern but in year four diminished greatly and to non-problematic levels. Though not conclusively confirmed I believe this to be due, in part to the occurrence of a granulovirus epidemic (Pfannensteil and Brunner,
2002). Substantiation of this phenomenon is needed. The capture of overwintering leafroller larvae in bands seemed to accurately reflect leafroller populations the following year. Year-four overwintering leafroller catches were substantially reduced suggesting that it might not routinely require therapeutic intervention for its management. It may also be that fall trapping of overwintering larvae may be a valuable predictive tool. Generalist predator populations increased somewhat during the four-year study and again cover crop did not appreciably influence that. Additionally, the make-up of generalist predator community populations changed in composition over the course of the study as indicated by observation of predators associated with aphid colonies and those caught in overwintering traps. Finally lygus bug, a particular concern with the use of its preferred host, alfalfa, as an orchard cover, did not achieve pest status in this study though populations in alfalfa plots did increase. Alternate row mowing may be an important lygus bug management tool when alfalfa plants are part of the orchard cover.
CHAPTER FIVE

COVER CROP EFFECT ON ORCHARD SOIL FERTILITY, TREE NUTRITION
AND TREE GROWTH AND DEVELOPMENT

Introduction

Ecologically based pest management in orchards has been the focus of much recent discussion and investigation. Proponents and investigators of ecologically based pest management, in orchards hope to achieve the development of stable agroecosystems that require significantly fewer inputs and that exist in states of homeostasis and are thus sustainable (Altieri, 1994). Additionally ecologically based pest management strategies are hoped to be less environmentally disruptive, safer and more socially acceptable than chemically based pest management (Lewis, et al., 1997, Hill, et al., 1999).

Norlund (1984) points out that one environmental manipulation used to affect biologically based pest management is the utilization of the cover crop as a field insectary to increase natural enemy numbers or make them more efficient. Examples are common and include providing sources of alternate, supplementary or complimentary herbaceous or animal foods, enhancing refugia, nesting sites, overwintering sites, and modifying climates (Bugg and Picket, 1998; Flint and van den Bosch, 1981; Norlund, 1984; Pedigo, 2002). Cover crops in orchards have been and are currently used for such purposes and investigations into such ensue (Altieri, 1994; Altieri and Letourneau, 1982; Altieri and Nickolls, 1999; Bugg and Waddington, 1994; Mills, 1992; Nickolls and Altieri, 2001).

Both Nickolls and Altieri (2001), and Stary and Pike (1999) suggest that one tactic (in addition to more judicious use of pesticides) to reverse the decline in natural control agents is to design and maintain orchard floor habitats to diversify the flora of the agroecosystem for natural
enemies. Undoubtedly groundcover within an orchard can influence interactions between beneficial arthropods and orchard pests (Prokopy, 1994). Tedders (1983) said that for deciduous tree crops, interplanting with other crops or cover crop plantings might have the broadest potential as a diversification/habitat management tool to affect beneficial elements within the agroecosystem and enhance pest control.

Ultimately, it is not simply a matter of vegetative diversity but a matter of “functional” diversity determined through investigation and experience (Southwood and Way, 1970). Numerous studies illustrate and document the potential application of plant composition manipulation and habitat design to enhance biological control of arthropod pests in tree fruit and the particular function related to specific crops and cropping circumstance (Brown et al., 1997; Bugg and Waddington, 1994; Rieux et al., 1999; Tedders and Schaefer, 1994). Much early work was done in Eastern Europe (former U.S.S.R.) and in Canada (Leius, 1967). Effects of cover crop manipulations on arthropod populations in orchard agroecosystems for biological arthropod pest management have been studied in citrus (Liang and Huang, 1994), pecan (Bugg and Dutcher, 1993; Bugg et al., 1991; Rice et al., 1998; Smith et al., 1994), grapes (Altieri and Schmidt, 1985; Daane and Costello, 1998) and tree fruit (Alston, 1994; Brown and Schmitt, 1996; Brown and van der Zwet, 1997; Coli, et al., 1994; Cossentine et al., 1996; Fye, 1983; Haley and Hogue, 1990; McClure et al., 1982; Niemczyk et al., 1996; Nyrop et al., 1994; Stanyard et al., 1997; Wyss, 1995). However effect on arthropod population dynamics is not the sole concern associated with the use cover crops.

Apple trees are considered poor competitors with understory plant species and cover crops affect soil fertility. As such cover crops and orchard floor management practices directly affect tree performance (Woolridge and Botha, 1991). The effect of competition is expressed in changes in
fruit production, tree growth or fruit quality (Forshey, 1988; Marsh et al., 1996; Marsh et al., 1998). The nature of an orchard floor cover and its management can have a profound influence on orchard performance and ease of operation (Connell et al., 2001; Elmore et al., 1989). In addition to potentially providing habitat for beneficial arthropod population diversification and enhancement, cover crop use in orchards has several benefits including mitigation of water runoff and soil erosion, increased water penetration, addition of organic matter, recycling of nitrogen, increased pH, hindrance of harmful weed establishment, ease of operations and dust reduction. However ground covers also compete with orchard trees for water, nutrients and possibly oxygen, reduce lateral rooting and degree of mychorrhization as well as other soil biotic activity, may offer flowers visited preferentially by insect pollinators to the detriment of fruit tree pollination (Forshey, 1988; Marsh et al., 1996; Nielson and Hogue, 1985; Skroch and Shribbs, 1986; Woolbridge and Harris, 1989) and may harbor detrimental vertebrate and invertebrate pests (Byers, 1984; Jaworska, 1996; Meagher and Meyer, 1990; Merwin et al., 1999). Ground covers also affect abiotic orchard factors such as ambient and soil temperatures, soil texture and compaction (Meagher and Meyer, 1990; Nielson et al. 1986). As such ground cover management in orchards have long been a subject of horticultural investigation as evidenced by the work of Bedford and Peckering (1914), Howard (1924), Blackmon and Barnette (1936), Neilson and Hogue (1985) and Marsh et al. (1996).

Nielson et al. (1984) compared sod and clean cultivated orchard floor management systems on ‘Golden Delicious’ nitrogen nutrition and tree growth. They found significant reductions in leaf nitrogen levels and trunk growth in trees with the sod orchard floor. Fruit was also smaller but firmer and more highly colored from trees in the sod floor plots due to nitrogen depletion by the sod. They concluded that nitrogen nutrition was highly responsive to orchard floor management. Competition from orchard floor plants is a particular concern for newly established and young
apple trees (Woolbridge and Harris, 1989). Nielson and Hogue (1985) compared four soil
management treatment effects on young dwarf 'Red Delicious' apple trees. One treatment was
full sod cover and the other three were some sort of understory vegetation reduction. Leaf
nitrogen concentration was reduced in sod cover treatment trees and total weight of fruit
harvested was smaller. They also observed a sod induced potassium : magnesium antagonism.
They said ground cover management strongly influenced early growth of the young apple trees
in their experiment. Shribbs and Skroch (1986) evaluated 12 ground cover systems on young
'Smoother Golden Delicious'. They found that cover significantly influenced relative growth
rates of trees, stem diameter, shoot length, leaf length and yield. Mulched, bare ground and
cultivated treatments had greater tree growth than cover crop treatments. The two leguminous
covers had greater tree growth than the grass and non- leguminous broadleaf covers. Woolridge
and Harris (1989) likewise determined that various cover crops negatively impacted young fruit
tree growth compared to a clean, weed free orchard floor maintained with herbicides. Meyer et
al. (1992) demonstrated that peach tree growth rate and survival was dramatically impacted by
the kinds of plants composing the orchard floor and that tree survival was greatest and growth
optimized with bare ground. Meagher and Meyer (1990) also evaluated different ground cover
strategies in peach orchards. Consistent with other reports, bare-ground plots resulted in greater
tree growth and yield than did alternatively managed, weedy plots. Leguminous, grass and
mixed herbaceous apple orchard understory covers were evaluated by Marsh et al. (1996) in New
Zealand. They found tree nitrogen levels to be higher in legume- covered orchards. Fruit
maturity was delayed, fruit nitrogen levels increased and fruit soluble solids and firmness levels
decreased in those blocks. No increase in incidence of storage disorders was detected however.
They said that these changes in fruit quality and maturity highlighted the importance of
leguminous understories as contributors to tree nutrition.
Others have reported the influence of orchard covers on critical abiotic factors. Nielson et al. (1986) compared sod-covered management with other apple orchard understory management strategies including total vegetation control with herbicides, shallow tillage and black plastic mulch. The full sod ground cover treatment resulted in the coldest soil during the growing season but the warmest during the winter and had the lowest yield. Similarly Meagher and Meyer (1990) also found bare ground orchard plots to have higher soil temperatures than those with sod or strip-sod covered understories. Additionally plant covered understories exhibit reduced soil moistures compared to bare understories (Nielson et al. 1986; Meagher and Meyer, 1990). Skroch and Scribbs (1986) relay that leguminous orchard covers reduce soil moisture availability more than grass covers do. Hogue and Nielson (1987) and Skroch and Scribbs (1986) reviewed effects of orchard floor vegetation management on fruit tree growth and development and on abiotic factors in orchards.

Some report increased incidence of insect pest damage associated with various orchard cover crops (Meagher and Meyer, 1990; Meyer et al. 1992; Skroch and Shribbs, 1986) but a major pest concern relative to orchard ground covers is field mice (*Microtus* sp.) which feed upon tree roots and trunks during the winter; cover crop shoot and leaf biomass production was a significant predictor of vole populations (Byers 1984; Merwin et al., 1999). Byers (1984) however, in his discussion of orchard cover crops for vole biological control, conveyed that several genetic lines of alfalfa have been shown to result in poor weight gain of voles due to poor acceptance as a food and/or the presence of antimetabolites. As such alfalfa may be a preferred leguminous orchard cover species.

Certain plants, mostly in the families Apiaceae, Compositae, and Leguminosae seemingly play an important ecological role by harboring and supporting a complex of beneficial arthropods that
contribute to pest suppression (Altieri, 1995; Stary and Pike, 1999) and the majority of orchard cover, habitat manipulation strategies employ them individually or in some combination. Economically useful species could include those providing multiple benefits. For example legumes are recognized as “stabilizing crops” used to improve soils and crop yields and to increase diversity of beneficials (Stary and Pike, 1999). In Washington State apple orchards grass covers are standard but there is interest in the use of alfalfa to improve soil quality and enhance the biological control of arthropod pests by providing alternate, herbaceous foods for insect parasitoids. There is also, however, considerable apprehension regarding possible adverse effects on tree growth and development with the use of alfalfa as a cover. Specific concerns include alfalfa being too competitive and the potential of alfalfa use to result in excessive soil and tree N levels.

As such the objectives of this study are to:

1. Evaluate the effect of alfalfa, used as an apple orchard cover crop, on tree growth and development, and

2. Evaluate the effect of alfalfa, used as an apple orchard cover crop, on soil fertility and tree nutrition.

**Materials and Methods**

Plots for this experiment were established in a 3.12-hectare, 5th leaf, mature-bearing Fuji (BC 2/M9) apple block in north central Washington. Trees in the block were planted at a spacing of 1.2m X 3.96m for an approximate density of 1,977 trees per hectare. They were trained to a modified HYTEC system typified by a central axis, conical shape and aggressive lateral renewal (Barritt, 1992) and supported on an upright, 3-wire, 3m high, trellis. The 3.12-hectare block was
divided into six contiguous plots varying in area from 0.49 to 0.57 hectare and containing from 1004 to 1056 trees each. A randomized block design was utilized for this experiment (Davis, 2000; Snedecor and Cochran, 1976). The three treatments each of alfalfa or grass covers were equally and randomly assigned to one of the six plots so that there was three replications of the grass cover treatment, designated plots G1, G2, and G3, and three replications of the alfalfa cover treatment, designated plots A1, A2, and A3 (see Appendix A). Thus there were three replicate blocks; each containing two experimental cover treatment plots. Both alfalfa and grass plots were sown with their respective cover cultivar on May 21 of 1999 the first year of the four-year experiment. A standard, commercially available grass orchard cover mix of perennial rye and red fescue was utilized for the grass cover treatment while ‘Vernal’, an older, drought tolerant, lower vigor cultivar, was utilized for the alfalfa cover treatment. A 1.52m wide, tree row, weed-free strip was maintained with annual applications of glyphosate herbicide per standard orchard management practice. The orchard block was farmed utilizing standard horticultural practices with the exception of insect pest management; in-season insecticide applications were eliminated. Ammonium nitrate fertilizer was band applied per standard recommendation and practice, at a uniform rate and at the same time in the early spring, to all plots in all years of the study (see appendix B). Boron and zinc foliar fertilizers were also applied to all plots in all years of this study per standard recommendation and practice. All plots were uniformly cultivated except when the maintenance of the two different covers dictated otherwise.
Cover crop composition and biomass N content

After the establishment year, in mid-summer, cover crop vegetation composition was evaluated. Ten individual, 1-meter (indicated by placement of a pre-made hoop) diameter sites were randomly selected in each plot and prevalent plant species were noted and recorded.

Cover N content was also estimated. To do so, in each plot, vegetation from three randomly selected sample sites was clipped at 15cm from soil level, collected and combined to create a homogenous sample. The three samples from each plot were submitted to a commercial laboratory, Cascade Analytical, Wenatchee, WA for N content analysis. In year three, when the cover stands were mature and full, N content per unit biomass was also estimated.

Soil fertility and plant nutrition assessment

The influence of the two cover treatments on soil N level, in both tree and drive rows of all plots, was assessed throughout the growing season by collecting and submitting soil samples for analysis in late March (before fertilizer application), early May (after fertilizer application), late summer (August/September) and early November. Spring and late summer (March, May and August/September) analysis was not done in the initial year of the experiment (done only for 2000, 2001 and 2002). However, November sample analysis was performed for all four years. For each spring/summer sample five cores were randomly collected from a depth of 0.0 to 30.5cm using a standard soil sampling tube, made into a composite sample and submitted to a commercial laboratory for analysis, Cascade Analytical, Wenatchee, WA.

Additionally the influence of the two cover treatments on overall soil fertility was also assessed for both tree and drive rows of each plot. Each November, after harvest, drive row and tree row
soil samples were collected with a standard soil sampling tube, at a depth of 0 to 30.5cm, for all plots. Ten individual, randomly collected core samples were obtained and mixed to make a composite sample. A commercial laboratory (Cascade Analytical, Wenatchee, WA) analyzed the samples for N, P, K, S, Mg, Ca, Mn, B, Zn, Mo, Cu, Fe, pH and organic matter (OM) content.

To assess tree nutritional status leaf tissue analysis was conducted for each plot. Samples were collected in mid-July of each year. Five mature leaves from each of 30 trees per plot were collected. The leaves were from healthy, moderately vigorous shoots at mid-canopy height and exposed to full sunlight. The samples were submitted to a commercial laboratory (Cascade Analytical, Wenatchee, WA) and analyzed for N, P, K, Ca, Mg, B, Zn, Fe, Cu and Mn content per standard horticultural practice.

**Tree growth and yield**

Tree growth was determined by measuring the circumference of tree trunks at 20cm above the graft union. Ten groups of five trees in each plot were selected for these measures and used each year of the experiment. However, many originally selected trees suffered severe winter injury in 1999-2000 and trees to replace them were planted in the spring of 2000. Trees for growth comparison were chosen for uniformity and as representative of the plot. Replant trees were not used. The exact point of measurement was marked on each sample tree in the initial year. Measurements were taken each year of the experiment in early spring (April) before the onset of bud break. To further characterize tree growth, shoot length measurements were taken at the end of the grand growth period, which is marked by the setting of terminal buds in the late summer. Ten trees, representative of the plot, were selected per plot and one uniformly representative branch on each of the ten trees was chosen for shoot measurement. For those branches shoot
lengths were measured and recorded for three shoot-type classifications; true terminal shoots, true lateral shoots; and bourse shoots.

Finally, total yield was estimated. For each plot, the bins of fruit harvested and sent to the packing shed was recorded. Also fruits culled in the field, at harvest, were also estimated for each plot and recorded. Total yield for each plot was calculated but adding estimated bins of field sorted fruit to those sent for packing.

Results and Discussion

Cover composition and nitrogen content

In the establishment year of the experiment the grass and alfalfa covers were very spotty and many endemic weeds became established and intermixed with the cover species creating a mixed grass-broadleaf cover in all plots of both treatments. However alfalfa dominated the alfalfa cover and grass dominated the grass cover treatment plots. In year two I initiated evaluation of cover crop composition. In the spring of year three I treated the grass plots with 2,4-D herbicide to reduce broadleaf plant presence. For both the alfalfa and grass plots the predominant weed species infesting the plots were sweet clover, *Melilotus* sp. (in grass plots only), dandelion, *Taraxacum vulgares* (Lam.) Schranks, foxtail, *Setaria* sp., and to a lesser extent lambsquarter, *Chenopodium album* L. (Table 5.1). In year two only 48% of the alfalfa plot cover crop was alfalfa with dandelion (28%) and foxtail (17%) substantially interspersed in the community of cover plants. By year three alfalfa came to dominate the cover (90%) with dandelion making up 10% of the cover crop species mix. Likewise in year two the perennial rye and fescue grass made up only 40% of the grass cover plots species mix with clover (8.7%), dandelion (21%) and giant foxtail (28%) being substantially intermingled. In year three the sown, perennial rye and fescue
Table 5.1. Composition of cover; percentage of dominant plant species in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Species</th>
<th>Alfalfa</th>
<th></th>
<th></th>
<th>Grass</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>alfalfa</td>
<td>48.0</td>
<td>89.9</td>
<td>96.0</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>rye/fescue</td>
<td>3.0</td>
<td>0.5</td>
<td>0.0</td>
<td>40.0</td>
<td>87.8</td>
<td>91.3</td>
</tr>
<tr>
<td>clover</td>
<td>0.0</td>
<td>0.0</td>
<td>0.3</td>
<td>8.7</td>
<td>0.7</td>
<td>4.0</td>
</tr>
<tr>
<td>dandelion</td>
<td>28.0</td>
<td>9.7</td>
<td>3.7</td>
<td>21.0</td>
<td>11.3</td>
<td>4.7</td>
</tr>
<tr>
<td>lambsquarter</td>
<td>4.0</td>
<td>0.0</td>
<td>0.0</td>
<td>2.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>foxtail</td>
<td>17.0</td>
<td>0.0</td>
<td>0.0</td>
<td>28.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
came to dominate the grass plots at 88% of the species mixture with the broadleaf, dandelion, still substantially present at 11% of the cover species make up. Clover was reduced in the grass plots to 0.7% of the species mix in year three. In year four the sown species, for all treatment plots created a substantially homogenous orchard cover. In alfalfa plots 96.0% of the surface was occupied by alfalfa. Dandelion and clover were the only other two species observed in the alfalfa plots and they constituted 3.7% and 0.3% of the cover respectively. In the perennial rye and fescue grass plots 91.3% was covered with the sown species. Again dandelion (4.7%) and clover (4.0%) were the only invasive species observed. It seems clear that alfalfa is sufficiently vigorous and competitive to form an orchard cover and to discourage invasive species to a very substantial extent. It may very well be that alfalfa is too competitive and will disallow the use of other plant species in the cover community to further enhance beneficial arthropod habitat and biological control.

Nitrogen content per unit biomass of the cover for both treatments was measured for the first three years until the stand became nearly homogenous. As expected the alfalfa cover, regardless of the degree of stand homogeneity, consistently had a significantly greater ($F= 146.32$, $DF= 1,4$, $P= > 0.001$; $F= 184.60$, $DF= 1,4$, $P= > 0.001$; $F= 163.50$, $DF= 1,4$, $P= > 0.001$ for years one, two and three respectively) nitrogen content (4.79% average over the three years) and hence the potential to contribute more nitrogen to the orchard system (Table 5.2). As alfalfa stand homogeneity increased so did N content per unit biomass. Grass cover N content (2.45% average over the three years) also rose but remained approximately half that of the alfalfa cover. Additionally biomass production was estimated and alfalfa, as anticipated, produced more (twice or better) biomass per unit area. It is evident that an alfalfa cover has potential to add substantial quantities of N to the orchard system.
Table 5.2. Percent nitrogen content per unit biomass in alfalfa and grass cover crop treatments, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>Grass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>4.59 a</td>
<td>2.16 b</td>
</tr>
<tr>
<td>2000</td>
<td>4.81 a</td>
<td>2.51 b</td>
</tr>
<tr>
<td>2001</td>
<td>5.05 a</td>
<td>2.71 b</td>
</tr>
</tbody>
</table>

Means followed by the same letter not significantly different ($P = 0.05$). See F values cited in the text. Treatments were compared for each year separately.
Soil Fertility, pH and organic matter

General soil fertility, in both the tree row and in the drive row for each plot, was assessed each fall by routine sampling technique and commercial laboratory analysis. Tree and drive rows were compared in recognition that dwarfing apple rootstocks (M9 in this case) are not particularly aggressive and tend to extend very little into the drive row. Additionally soil nitrate nitrogen level was assessed three additional times during the growing season; pre-fertilizer application (March), post fertilizer application (May) and August-September for years two, three and four (Table 5.3).

In November of year one, post-harvest soil nitrogen levels for both tree and drive rows in both treatments were relatively low, as one would expect. The subsequent spring (year two) nitrogen levels were even lower (all below 1.0 ppm), again as one would expect in a sandy loam soil. Summer analysis in year two indicated a similar and anticipated post-fertilizer application rise in nitrate levels in both alfalfa and grass tree rows. Though possibly slightly on the high side for the cultivar Fuji, levels were horticulturally acceptable. November analysis in year two revealed a substantial increase in soil nitrate levels in the alfalfa treatment, (25.4 ppm in the tree row and 6.2 ppm in the drive row) over the grass treatment. Twenty-five ppm of nitrate nitrogen at this time of year is considered very high and undesirable. Nitrate levels in the grass treatment also increased in the late November sample but only slightly and to levels well within an acceptable and expected range. Ammonium nitrate fertilizer was applied to young replant trees in all plots in early July and it may be that the alfalfa sample submitted for analysis was inadvertently obtained in too close proximity to where that fertilizer had been applied. It may also be that mowed alfalfa was deposited in the tree row and mineralization of nitrogen from the decomposing plant matter contributed to the elevated nitrate level though that seems unlikely in
Table 5.3. Soil nitrate nitrogen levels (ppm) for four different sampling times in tree rows and drive rows in alfalfa and grass cover plots, by year. *

<table>
<thead>
<tr>
<th>March</th>
<th>May</th>
<th>September</th>
<th>November</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tree row</td>
<td>Drive row</td>
<td>Tree row</td>
</tr>
<tr>
<td></td>
<td>af</td>
<td>gr</td>
<td>af</td>
</tr>
<tr>
<td>1999</td>
<td>1.16</td>
<td>8.83</td>
<td>1.56</td>
</tr>
<tr>
<td>2000</td>
<td>0.53</td>
<td>0.83</td>
<td>0.93</td>
</tr>
<tr>
<td>2001</td>
<td>1.26</td>
<td>1.40</td>
<td>0.90</td>
</tr>
<tr>
<td>2002</td>
<td>0.63</td>
<td>1.00</td>
<td>1.10</td>
</tr>
</tbody>
</table>

*af = alfalfa, gr = grass
such a short time span. March analysis in year three, revealed normal and expectedly lower nitrate levels in the tree row and in the drive row for both treatments (between 0.9 and 2.1 ppm). Later spring (after fertilizer application) and summer sample analyses revealed uniformly and expectedly higher soil nitrate nitrogen levels. There was no significant difference in N levels between alfalfa and grass treatments in the tree row or in the drive row for either sampling time. Levels ranged between 4.7 ppm and 6.6 ppm in the tree rows and between 2.2 ppm and 6.4 ppm in the drive rows for these two sampling times. November, year three tree row nitrate levels were again fairly high for alfalfa (19.8 ppm) though not as high as the previous year while grass nitrate levels were not excessive. Alfalfa drive row nitrate levels were extremely high (56.5 ppm) while grass drive row levels were much lower (4.4 ppm). The 56.5 ppm nitrate nitrogen level in the alfalfa drive row was substantially greater than drive row levels in previous years. Both tree row and drive row levels in the alfalfa treatment were higher than would be desired. It seems clear that the alfalfa in the drive row was fixing atmospheric nitrogen, which was subsequently mineralized and rendered available in the soil environment. It is less clear if the high tree row nitrogen levels are a direct result of the alfalfa cover. Persistent high drive row and in turn, high tree row nitrate nitrogen levels, would have a profound effect on tree growth and development particularly in relation to the balance between vegetative and reproductive growth and fruit quality. High nitrogen levels promote vegetative growth at the expense of reproductive growth (Elfving, 1996). Excess nitrogen delays fruit maturity and impedes fruit pigment synthesis in the fall (Johnson, 1996). Additionally high tree nitrogen levels in the fall interfere with tree acclimation and hardening off. In general, fall soil analysis for all other primary, secondary and micro- nutrients indicated no unusual conditions or occurrences (Table 5.4). Phosphorus levels for both tree and drive row generally fell within acceptable and normal ranges for all years though in grass tree row measures were somewhat low in year four. No meaningful differences were detected.
Table 5.4. Results of complete soil analysis for tree rows and drive rows in alfalfa and grass cover plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Tree row alfalfa</th>
<th>Tree row grass</th>
<th>Drive row alfalfa</th>
<th>Drive row grass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1999</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrate ppm</td>
<td>2.66</td>
<td>8.83</td>
<td>1.57</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>25.4</td>
<td>0.96</td>
<td>6.23</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>19.83</td>
<td>11.47</td>
<td>56.50</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>1.37</td>
<td>0.47</td>
<td>29.53</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6.40</td>
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<tr>
<td>Phosphorous ppm</td>
<td>8.23</td>
<td>7.43</td>
<td>8.06</td>
<td>7.77</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>12.87</td>
<td>5.60</td>
<td>9.97</td>
</tr>
<tr>
<td></td>
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<tr>
<td></td>
<td>2002</td>
<td>9.97</td>
<td>2.67</td>
<td>12.83</td>
</tr>
<tr>
<td>Potassium ppm</td>
<td>183.80</td>
<td>126.80</td>
<td>291.67</td>
<td>239.00</td>
</tr>
<tr>
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<td>198.33</td>
<td>168.67</td>
<td>379.67</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>288.67</td>
<td>196.33</td>
<td>457.33</td>
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<td>2002</td>
<td>169.33</td>
<td>157.33</td>
<td>507.33</td>
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<tr>
<td>Calcium ppm</td>
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<td>1260.00</td>
<td>291.67</td>
<td>239.00</td>
</tr>
<tr>
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<td>198.33</td>
<td>168.67</td>
<td>379.67</td>
</tr>
<tr>
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<td>959.00</td>
<td>168.67</td>
<td>379.67</td>
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<tr>
<td></td>
<td>2002</td>
<td>835.00</td>
<td>168.67</td>
<td>379.67</td>
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<tr>
<td>Magnesium ppm</td>
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<td>770.67</td>
<td>740.00</td>
<td>736.33</td>
</tr>
<tr>
<td>Sulfate- S ppm</td>
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<td>5.00</td>
<td>2.37</td>
<td>1.87</td>
</tr>
<tr>
<td></td>
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<td>6.03</td>
<td>5.07</td>
<td>5.33</td>
</tr>
<tr>
<td></td>
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<td>7.10</td>
<td>6.10</td>
<td>6.10</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>2.10</td>
<td>2.00</td>
<td>5.17</td>
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<tr>
<td>Boron ppm</td>
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<td>152.00</td>
<td>154.33</td>
<td>185.67</td>
</tr>
<tr>
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<td>144.00</td>
<td>146.00</td>
<td>167.00</td>
</tr>
<tr>
<td></td>
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<td>122.77</td>
<td>123.33</td>
<td>132.93</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>116.50</td>
<td>113.67</td>
<td>118.33</td>
</tr>
<tr>
<td>Magnesium ppm</td>
<td>2.20</td>
<td>2.00</td>
<td>5.17</td>
<td>3.20</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>6.03</td>
<td>5.07</td>
<td>5.33</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>7.10</td>
<td>6.10</td>
<td>6.10</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>2.10</td>
<td>2.00</td>
<td>5.17</td>
</tr>
<tr>
<td>Copper ppm</td>
<td>0.14</td>
<td>0.21</td>
<td>0.60</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>0.60</td>
<td>0.30</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>0.40</td>
<td>0.53</td>
<td>0.20</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>0.18</td>
<td>0.18</td>
<td>0.10</td>
</tr>
<tr>
<td>Zinc ppm</td>
<td>0.67</td>
<td>0.73</td>
<td>0.66</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>0.63</td>
<td>0.70</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>0.67</td>
<td>0.63</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>0.63</td>
<td>0.37</td>
<td>0.43</td>
</tr>
<tr>
<td>Manganese ppm</td>
<td>1.40</td>
<td>1.50</td>
<td>1.40</td>
<td>1.50</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>4.20</td>
<td>3.10</td>
<td>4.20</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>2.20</td>
<td>2.53</td>
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</tr>
<tr>
<td></td>
<td>2002</td>
<td>1.57</td>
<td>1.17</td>
<td>1.57</td>
</tr>
<tr>
<td>Iron ppm</td>
<td>1999</td>
<td>3.97</td>
<td>3.87</td>
<td>3.70</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>5.93</td>
<td>4.53</td>
<td>5.50</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>7.30</td>
<td>6.73</td>
<td>5.60</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>2.96</td>
<td>4.87</td>
<td>4.50</td>
</tr>
<tr>
<td></td>
<td>1999</td>
<td>19.63</td>
<td>16.10</td>
<td>20.03</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>24.83</td>
<td>17.90</td>
<td>22.10</td>
</tr>
<tr>
<td></td>
<td>2001</td>
<td>24.50</td>
<td>23.47</td>
<td>33.07</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>16.90</td>
<td>17.73</td>
<td>19.70</td>
</tr>
</tbody>
</table>
Potassium levels also generally fell in or above optimal ranges but represented nothing unusual or unacceptable for both tree and drive rows in all years. Again no meaningful differences were measured. Calcium and magnesium levels consistently fell within optimal ranges and were not practically different between treatments for any year in either tree or drive rows. Tree and drive row sulfate-sulfur levels for both treatments were consistently below optimal ranges in the first year of the experiment. In years two and three levels were acceptable for both drive and tree rows for both treatments with no meaningful differences, between treatments, measured. Microfine sulfur and ammonium thiosulfate were applied to all plots in year three which likely accounts for the singularly high sulfate level detected in the grass drive row treatment in that same year. In year four sulfate levels again dropped to near year one levels. Low soil sulfate levels are not unusual in Central Washington and with decreased use of sulfur-containing fungicides sulfur deficiencies are increasingly commonplace. Apple trees have a particularly high demand for the micronutrients zinc, iron and boron. Boron and zinc were applied to experimental plots each year per standard horticultural practice in Washington State. Measures of the micronutrients iron, zinc, boron, manganese and copper indicated no adverse condition. With the exception of boron, for all, levels fell within optimal ranges and no meaningful differences existed between treatments, in tree and drive rows, for all years. Boron levels were intermittently below minimum range, a condition typical of soils in Central Washington. No meaningful differences between treatments in any year, in either the tree or drive rows existed. Finally, copper and manganese levels also consistently fell within acceptable ranges and there were no meaningful differences between treatments in either the tree or drive rows for any year.

Soil organic matter content throughout the course of the study and for both cover treatments remained fairly constant and low at about 1% (Table 6.5). The highest tree row levels for both treatments were measured in year four but the highest drive row level for grass was in year one.
Table 5.5. Percent soil organic matter content in tree and drive rows for alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa tree row</th>
<th>Grass tree row</th>
<th>Alfalfa drive row</th>
<th>Grass drive row</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>0.80</td>
<td>0.63</td>
<td>1.23</td>
<td>1.47</td>
</tr>
<tr>
<td>2000</td>
<td>0.96</td>
<td>0.83</td>
<td>0.93</td>
<td>1.16</td>
</tr>
<tr>
<td>2001</td>
<td>1.00</td>
<td>0.80</td>
<td>0.83</td>
<td>0.97</td>
</tr>
<tr>
<td>2002</td>
<td>1.07</td>
<td>1.13</td>
<td>1.27</td>
<td>1.17</td>
</tr>
</tbody>
</table>
It is typical of arid northwest solids to have soil organic matter contents of 1-2%. It is somewhat surprising that the alfalfa cover did not result in an increase in organic matter content levels. It may be that more time would be necessary for measurable and significant increases to result at the depths sampled. For each year of the experiment there was no practical difference in either the tree row or drive row soil organic matter content between treatments. The tree row soil organic matter content was greatest for both the alfalfa and grass treatment in year four (1.07% and 1.13% respectively) and lowest for both (0.80% and 0.63% respectively) in year one. Of course very little vegetation was permitted to grow in the weed free strip underneath the trees so it is not surprising that organic matter levels were low. The highest drive row organic matter content levels were measured in year one (1.47% for grass and 1.23% for alfalfa) which was likely the result of incorporation of plant material in the course of soil tilling that spring, in preparation for cover seed sowing. It does not seem, at this point, that alfalfa contributes to the inclusion of more organic matter in the soil than does grass though given the amount of biomass alfalfa generally produces in comparison with grass that is not an unreasonable expectation. If alfalfa cover is to contribute to increased organic matter levels in orchard soils it may take some time to realize the gain.

Soil pH also remained fairly constant for both cover treatments, in the drive and tree rows, for both treatments, throughout the duration of this study (Table 5.6) and were at acceptable levels except in year three when alfalfa treatment tree and drive row pH was lower than for any other measure during the coarse of the study. From a management perspective these low pH levels were not problematic and had they persisted could readily be remedied by liming per normal management procedure. The application of micro-fine sulfur and ammonium thiosulfate in the spring of that year likely accounts for the drop in soil pH. The low soil pH also, in all likelihood,
resulted in increased iron solubility and hence the generally higher iron levels detected in year three. In year four pH levels, for the tree row and drive row, for both treatments returned to near optimal levels.

Over my four-year study it was evident that the alfalfa cover did not adversely affect soil nutrient status. It seems equally evident that the alfalfa, possibly with the exception of nitrate-N did not enhance soil nutrient content in any particular way. Assessment of nitrate-N contribution by an alfalfa cover will require longer-term study.

Leaf tissue analysis

Leaf tissue analysis results indicated a generally acceptable nutritional status for trees in both cover treatments for all years (Table 5.7). No significant (power of the test values were generally quite low and as such it may that the test to detect differences between cover crop treatments may simply have not been strong enough to do so if they existed) or practical differences between treatments were found for any element. Leaf nitrogen levels were slightly higher for both alfalfa and grass plots in years two and three; the likely result of a urea foliar application. The high foliar tissue N levels in year three coincided with the particularly high soil nitrate levels in November of that same year. However, year three soil nitrate levels of samples proceeding leaf tissue collection were not unreasonably elevated. For all years there was no difference in nitrogen content between treatments. The high level of tissue nitrogen proved transitory and did not seem to contribute to excess vigor or delay of fruit maturity. The low zinc levels persistent throughout the study are typical of apple orchards in Central Washington. Zinc is applied annually to most Washington orchards.
Table 5.6. Soil pH for tree and drive rows in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th></th>
<th>Alfalfa tree row</th>
<th>Grass tree row</th>
<th>Alfalfa drive row</th>
<th>Grass drive row</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>6.67</td>
<td>6.73</td>
<td>6.80</td>
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<td>2000</td>
<td>6.93</td>
<td>6.90</td>
<td>6.80</td>
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<td>6.06</td>
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<tr>
<td>2002</td>
<td>6.77</td>
<td>6.83</td>
<td>6.63</td>
<td>7.03</td>
</tr>
</tbody>
</table>
Table 5.7. Leaf tissue analysis for alfalfa and grass cover crop plots, by year*

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Year</th>
<th>Alfalfa</th>
<th>Grass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen %</td>
<td>1999</td>
<td>2.40 a</td>
<td>2.08 a</td>
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<td>2000</td>
<td>2.51 a</td>
<td>2.48 a</td>
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<td>2001</td>
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<td>2.87 a</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>2.27 a</td>
<td>2.27 a</td>
</tr>
<tr>
<td>Phosphorous%</td>
<td>1999</td>
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<td>0.19 a</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>0.20 a</td>
<td>0.21 a</td>
</tr>
<tr>
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<td>2001</td>
<td>0.20 a</td>
<td>0.20 a</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>0.16 a</td>
<td>0.15 a</td>
</tr>
<tr>
<td>Potassium %</td>
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<td>1.87 a</td>
</tr>
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<td>Calcium %</td>
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<td>1.69 a</td>
</tr>
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<td></td>
<td>2002</td>
<td>1.90 a</td>
<td>1.63 a</td>
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<td>2002</td>
<td>0.29 a</td>
<td>0.29 a</td>
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<td>37.67 a</td>
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<td>32.67 a</td>
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<td>2002</td>
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</tr>
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</tr>
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<td>2000</td>
<td>14.00 a</td>
<td>11.67 a</td>
</tr>
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<td></td>
<td>2001</td>
<td>13.33 a</td>
<td>12.67 a</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>14.00 a</td>
<td>12.67 a</td>
</tr>
<tr>
<td>Manganese ppm</td>
<td>1999</td>
<td>36.33 a</td>
<td>46.33 a</td>
</tr>
<tr>
<td></td>
<td>2000</td>
<td>38.67 a</td>
<td>39.00 a</td>
</tr>
<tr>
<td></td>
<td>2001</td>
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<td>36.33 a</td>
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<tr>
<td></td>
<td>2002</td>
<td>38.33 a</td>
<td>38.33 a</td>
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<tr>
<td>Copper ppm</td>
<td>1999</td>
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<td>7.33 a</td>
</tr>
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</tr>
<tr>
<td></td>
<td>2001</td>
<td>7.33 a</td>
<td>7.00 a</td>
</tr>
<tr>
<td></td>
<td>2002</td>
<td>5.67 a</td>
<td>5.67 a</td>
</tr>
</tbody>
</table>

*Each nutrient element analyzed separately. Means followed by the same letter not significantly different (P = 0.05). See F values cited in the text. Treatments were compared for each year separately.
Tree growth and development

Trees in both cover treatments grew steadily and seemed to grow equally well during this study (Table 5.8). Trunk circumference for both covers in each year of the study did not statistically differ from one another (power of the test = 0.143, 0.052, 0.052 and 0.10 for years one, two, three and four respectively). Interestingly, trunk circumference for alfalfa cover treatment trees was consistently greater than for grass treatment trees in all four years.

Commensurate with the annual increases in trunk circumference (Table 5.8), mean total terminal shoot length increased throughout the term of the study for both treatments (Table 5.9). Both grass and alfalfa cover trees, in year four, exhibited the greatest terminal shoot growth. Terminal shoots on alfalfa treatment trees were significantly longer than those in the grass cover treatment that year ($F= 15.88; \text{DF}= 1,58; p< 0.001$). Alfalfa plot tree terminal shoots were also significantly longer the previous year ($F= 9.07; \text{DF}= 1,58; p= 0.003$). For other years there was no significant difference between cover crop treatments (power of the test = 0.08 and 0.05 for years one, two respectively). In general, alfalfa cover treatment terminal shoots tended to be longer than grass cover treatment shoots. Similarly, in year three and year four, mean total lateral shoot length was greatest for alfalfa cover treatment trees. In years one, two and four alfalfa cover plot lateral shoot growth was not significantly greater (power of the test = 0.05, 0.25 and 0.8 for years one, two and four respectively) than grass cover trees but in year three it was ($F= 107.25; \text{DF}= 1,58; p< 0.001$). Again, both may be indicative of the of the alfalfa cover invigorating trees via elevation of soil nitrate levels. For three of the four years there was no difference in mean total bourse shoot length between treatment trees.

Yields (see chapter three for total yield estimation) for both treatments in all years, though fluctuating somewhat (Fuji is an alternate bearing cultivar), fell within anticipated and acceptable
Table 5.8. Trunk circumference of apple trees in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Alfalfa</th>
<th>Grass</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>16.04 a</td>
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<tr>
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<td>2001</td>
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</tr>
<tr>
<td>2002</td>
<td>21.80 a</td>
<td>21.18 a</td>
</tr>
</tbody>
</table>

Means followed by the same letter not significantly different ($P = 0.05$). Treatments were compared for each year separately.
Table 5.9. Mean terminal, lateral and bourse shoot length (cm) of apple trees in alfalfa and grass cover crop plots, by year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Terminal</th>
<th></th>
<th>Lateral</th>
<th></th>
<th>Bourse</th>
<th></th>
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<td></td>
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<td></td>
<td>Alfalfa</td>
<td></td>
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<tr>
<td></td>
<td>Grass</td>
<td></td>
<td>Grass</td>
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<tr>
<td>1999</td>
<td>35.72 a</td>
<td></td>
<td>17.82 a</td>
<td></td>
<td>19.22 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>33.37 a</td>
<td></td>
<td>18.24 a</td>
<td></td>
<td>18.51 a</td>
<td></td>
</tr>
<tr>
<td>2000</td>
<td>45.83 a</td>
<td></td>
<td>24.70 a</td>
<td></td>
<td>21.70 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>47.67 a</td>
<td></td>
<td>24.47 a</td>
<td></td>
<td>21.32 a</td>
<td></td>
</tr>
<tr>
<td>2001</td>
<td>52.10 a</td>
<td></td>
<td>35.67 a</td>
<td></td>
<td>13.77 b</td>
<td></td>
</tr>
<tr>
<td></td>
<td>40.57 b</td>
<td></td>
<td>13.03 b</td>
<td></td>
<td>32.10 a</td>
<td></td>
</tr>
<tr>
<td>2002</td>
<td>66.13 a</td>
<td></td>
<td>29.60 a</td>
<td></td>
<td>11.70 a</td>
<td></td>
</tr>
<tr>
<td></td>
<td>57.67 b</td>
<td></td>
<td>29.23 a</td>
<td></td>
<td>11.60 a</td>
<td></td>
</tr>
</tbody>
</table>

Means followed by the same letter not significantly different ($P = 0.05$). See F values cited in the text. Treatments were compared for each year separately. Shoot classes were analyzed separately.
ranges. Cover treatment did not affect yield during the course of this study though yields were somewhat higher for the alfalfa treatment than the grass treatment in all years. This may be attributable to the slightly more vigorous state of the alfalfa treatment trees. Yield is a function of canopy size, fruiting wood quality (which comes/is renewed from vegetative growth) and (moderate) vigor. Bitter pit, is a physiological disorder of apple fruits associated with low calcium content of the fruit, excessive tissue nitrogen levels and heat stress. One frequently expressed concern regarding the use of legumes as cover crops in orchards is excess nitrogen and the potential for bitter pit. I evaluated cull fruit to assess the incidence of bitter pit. In year two bitter pit incidence (for both treatments with no difference between treatments) was higher than in the other years. It was a very hot growing season. Similarly, in the other years was not a significant difference between treatments in the incidence of bitter pit. There is no indication that the cover influenced the incidence of bitter pit and in no year of the experiment, regardless of significant differences, was bitter pit incidence of practical concern. Likewise, the incidence of fruit russetting, another physiological disorder of concern, that is influenced by the orchard environment and causes a net-like scarring of the fruit epidermis, was not significantly greater for the alfalfa cover treatment than for the grass treatment any year of the study and was not of any practical concern at any time.

Conclusion

The cover crops became established and dominant after two years. An essentially homogenous stand resulted. Dandelion and clover were the predominant invasive species. Alfalfa produced more biomass and that biomass contained approximately twice the nitrogen content compared to grass on a per unit basis. Though not overwhelming, it was evident that trees in the alfalfa treatment were subject to elevated nitrogen levels. Compared to grass treatment trees they
demonstrated delayed leaf senescence and slightly more vegetative growth (Figures 5.1 and 5.2). Fruit quality and maturity was not affected though no specific procedure was undertaken to quantify the observation. In fact, the alfalfa plot trees generally had higher yields than grass plot trees. Soil fertility and pH status, with the exception of nitrogen, was essentially the same between the two treatments. Nitrogen levels fluctuated from fall highs to early spring lows (from winter leaching) for both treatments. As a result early springtime nitrogen fertilizer applications were necessary for both treatments during the study. After four years spring nitrogen applications may no longer be necessary for the alfalfa cover. Fall soil nitrate nitrogen levels for alfalfa plots came to be very high which likely accounts for the delayed leaf senescence observed. It may be that an orchard with an alfalfa cover crop will suffer from excessive nitrogen over time but that was not demonstrated in the four years of this study. Interestingly, organic matter levels were not improved in the alfalfa plots despite their production of large quantities of biomass. Soil pH did not differ between treatments and was at acceptable levels throughout the study. Likewise leaf tissue analysis revealed no practical differences between cover treatments and no unacceptable or unanticipated levels of nutrient elements. Trees grew equally well in both cover treatments. Alfalfa cover plot trees were consistently, albeit only slightly, larger each year of the study than were grass cover plot trees. Additionally terminal and lateral shoot extension was greatest for alfalfa cover tree. Both indicate an overall invigoration of alfalfa plot trees. Whether that invigoration will prove to be excessive is beyond the temporal scope of this study.

Alfalfa plot trees yielded more fruit than grass plot trees, which may be a result of their slightly elevated vigor. Excess vigor would have the opposite effect. Ultimately the alfalfa cover did not adversely affect tree growth and development compared to the standard grass cover. It may be
Figure. 5.1. Experimental block - note lighter green color of grass plot in center of photograph. Below and above the grass plot are alfalfa plots exhibiting darker green color indicative of higher nitrogen content in the fall.
Figure 5.2. Grass plot trees in the right foreground. Alfalfa plot trees in the left foreground and far center of the photograph. Note lighter green color of the grass plot trees and darker green color of alfalfa plot trees. Photograph taken fall 2002.
that the alfalfa cover enhanced tree performance and would over time demonstrate itself a superior apple orchard cover crop.

It must be noted that there were many non-significant, equivocal results as indicated by very low power of the test values. It may very well be that the tests were not strong enough to detect differences between cover crop treatments if they existed. This shortcoming arose from having only three treatment replicates. The larger, 0.5 ha plot sizes (instead of more, smaller plots) were a calculated compromise intended to mitigate potential small plot size effect on arthropod community population dynamics and to better approximate an agricultural environment.
CHAPTER SIX

GENERAL CONCLUSIONS AND DIRECTIONS FOR FUTURE INVESTIGATION

Conclusions

Increasingly, Washington apple (*Malus domestica* Borkh) growers are utilizing mating disruption for the management of codling moth (*Cydia pomonella*). One noted result is the emergence of leafrollers as a serious and economically important pest (Alway, 1996b; Brunner, 1991; Knight et al., 1998; Walker and Welter, 2001). Additionally, leafrollers are reported to be increasingly resistant to organophosphate insecticides (Brunner, 1991; Carriere et al., 1996; Croft, 1982; Madsen and Carty, 1977). Simultaneously, the use of organophosphate and other insecticides in agriculture has come under intense scrutiny and is increasingly questioned from, amongst others, environmental and food safety standpoints by agriculturists, consumers and activists alike (Benbrook, 1996; Fretz, 1993; Lewis et al., 1997; Kimber, 2002; National Research Council, 1996; Stauber et al., 1995). There is a call to investigate and develop biologically/ecologically based pest management systems that eschew pesticides and rely primarily on agroecosystem design and inherent biological control agents as the preferred and premiere pest management tool (Hill et al., 1999; Lewis et al., 1997; National Research Council, 1996; Prokopy, 1994). The advent of codling moth mating disruption, coupled with the availability of new, selective insecticidal materials in apple orchards, creates an unprecedented opportunity to do so.
The study reported in the proceeding chapters was designed to evaluate the effect of an alternative cover crop, alfalfa (compared to a standard grass cover) in an apple orchard in which broad-spectrum insecticides applications had been eliminated on 1) the population dynamics of leafrollers and their parasitoids, 2) the potential for biological control of apple leafrollers by a parasitoid complex, 3) the dynamics of selected orchard arthropod populations exposed to different cover crops and a soft pest management regime, 4) the impact of an alfalfa cover on selected aspects of the orchard environment and on apple tree growth and development and 5) the potential to conserve and augment the leafroller parasitoid *Colpoclypeus florus*,

Cover crop establishment was accomplished the first year of the study and by year three stands provided an essentially homogenous habitat. Dandelion and clover were the dominant invasive species for both covers but did not constitute a substantive portion of either cover treatment.

In the absence of broad-spectrum insecticides, *Pandemis pyrusana* Kearfott densities quickly increased in both alfalfa and grass cover treatments. By the third year *P. pyrusana* densities exceeded 40% infestation of the tight cluster buds and nearly 100% of terminal shoots in the summer. However, in the fourth year *P. pyrusana* populations declined dramatically. In the spring of year four, tight cluster infestations were approximately 5%, which approached those at the beginning of the experiment, and summer shoot infestations were also low. The best explanation for the precipitous decline was to the effects granulosus virus epidemic (Pfannensteil and Brunner, 2002).
Neither the grass or alfalfa cover was found to appreciably affect leafroller populations. 

*P. pyrusana* was attacked by a complex of parasitoids that, to a limited extent, contributed to reduction in leafroller densities. Parasitism rates lagged behind *P. pyrusana* population growth. Predation by generalist predators such as earwigs, *Forficula auricularia* (Linnaeus) and spiders (Araneae) also may have contributed to the decline in leafroller densities. Many spiders and earwigs were detected in leafroller retreats, observed in limb-tap samples and were collected in overwintering band traps. Overwintering generation leafroller trap catch was greatest in the winter preceding peak population levels in the third year. Overwintering generation trap catch could prove to be a valuable predictive tool.

The six parasitoids reared from both *P. pyrusana* and sentinel obliquebanded larvae were a tachinid species, two *Apanteles* spp., two *Bracon* spp. and *C. florus*. The complex of leafroller parasitoids was more extensive than anticipated. Tachinids seemed to exhibit a preference for obliquebanded leafroller and were most prevalent in the early season in association with that host rather than with *P. pyrusana*. There may be potential for further augmentation of tachinids to enhance biological control of the overwintering leafroller generation especially for obliquebanded leafroller. Braconidae were the dominant early season parasitoid of *P. pyrusana*. Braconidae were also the dominant mid-season parasitoid of both *P. pyrusana* and obliquebanded leafrollers. *C. florus* was not detected parasitizing either leafroller species until late summer and early fall. The preponderance of parasitism throughout these studies was by Braconidae sp. As such it would seem that there also is opportunity to enhance the activity of Braconidae sp. as a leafroller biological control agent. The fact that *C. florus* was not a significant factor in
the biological control of leaf rollers and that it’s presence was limited to the late summer and fall supports the understanding that it does not overwinter in the orchard or in association with orchard leaf rollers (Brunner, 1996; Evenhuis and Vlug, 1983; Gruys and Vaal, 1984). Without more substantive conservation and augmentation effort it may have more limited potential for early season leaf roller biological control than previously thought (Alway, 1997a; Beers et al. 1993; Pfannensteil et al., 1997).

Though not directly tested it seems clear that over the course of the four-year study the elimination of in-season, broad-spectrum insecticides promoted survival of leaf roller biological control agents and ultimately resulted in a reduction of the pest’s population to essentially non-pest status. In year-four of the study economic injury to fruit due to leaf rollers was negligible. Whether the population level achieved in year-four represents the lower population limit attainable or if homeostasis and hence a sustainable level of leaf roller biological control has been achieved has not been determined. It is also clear that the utilization of alfalfa as an orchard cover did not, in and of itself, appreciably enhance the presence or activity of leaf roller parasitoids. Different and various habitat management tactics, each designed to enhance specific parasitoids and collectively the complex of parasitoid species attacking orchard leaf rollers may be called for and might be more likely to result in higher levels of leaf roller biological control and achievement of parasitoid-host equilibrium at low leaf roller population levels (Altieri, 1994; Altieri and Nickolls, 1999; Bugg and Pickett, 1998).

Other secondary arthropod pests, commonly associated with apple production in the northwest (Beers, 1998; Beers et al., 1993), never achieved economic-pest status in the insecticide-free orchard environment in either cover crop treatment. Species evaluated
included mullein bug, *Campylomma verbasci* (Meyer), western flower thrips, *Frankliniella occidentalis* (Pergande), consperse and green stinkbugs, *Euschistus conspersus* Uhler and *Acrosternum hilare* (Say), green apple aphid, *Aphis pomi* De Geer, apple grain aphid *Rhapalosiphum fitcii* (Sanderson), rosy apple aphid *Dysaphis plantaginea* Passerini, white apple leafhopper *Tyhlocyba pomaria* McAtee, western tentiform leafminer *Phyllonorycter elmaella* Doglanar & Matuura as well as the spider mite complex. Though there were some modest differences between cover crop treatments for certain pests none were of practical significance. Concomitantly an increase in many generalist predators was observed in the orchard during the course of the studies. This phenomenon supports the contention that many pests of agriculture crops are pesticide induced (Flint and van den Bosch, 1981) and many apple pests reach problematic levels only because pesticides eliminate their natural enemies (Croft, 1982).

Again there was no practical difference in secondary pest incidence or generalist predator observation between the two cover treatments. Lygus bug, *Lygus lineolaris* (Palisot de Beauvois), a singularly prevalent and serious pest of alfalfa was never problematic, though populations did reach their highest levels in alfalfa plots the last year of the experiment. It would seem that lygus bug did not move from the cover to the apple canopy in excessive numbers. Alternate row mowing, with a minimum of one week between rows mowed, was intended to discourage the migration of lygus bug to the trees. Whether that was a positive factor and discouraged lygus bug movement from the orchard floor is unknown.

Codling moth, however, in the absence of broad-spectrum insecticides, did manifest itself as the key arthropod pest (as it has long been regarded) when pheromone-based mating
disruption as a stand-alone management strategy failed in year-four. Substantial losses were incurred. They could have been avoided if supplemental control measures had been employed. Whereas the elimination of broad-spectrum insecticides seemingly benefited the biological control of the breadth of secondary pests, it rendered the management of this key pest more difficult. The challenge will be to achieve adequate levels of codling moth control without disrupting the biological control of the other pest species including leafrollers. It is likely that multiple "soft", more ecological benign strategies, such as granulosus virus and dormant oil treatment in conjunction with mating disruption can be used to do so.

Both strategies to augment \textit{C. florus} populations and enhance leafroller parasitism were not successful. Strawberry plants infested with \textit{C. florus}-parasitized strawberry leaf rollers (\textit{Ancylis comptana fragaria}) did not appreciably increase the rate of \textit{P. pyrusana} parasitism by \textit{C. florus} in either cover crop treatment. Almost no \textit{C. florus} were reared from \textit{P. pyrusana} collected from apple trees in the vicinity of release sites. Augmentation rates where relatively low, so it may be that there simply were insufficient \textit{C. florus} introduced into the orchard to see an effect. Likewise the attempt to establish the alfalfa leafroller, \textit{Xenotemna pallorana}, to serve as an alternate host for \textit{C. florus} was unsuccessful. Despite repeated, controlled, seeding with adult male and female \textit{X. pallorana} very few egg masses or larvae were detected in alfalfa and nearly none in grass plots. A proliferation of generalist predators, encouraged by the absence of broad-spectrum insecticide use, in the alfalfa cover may have precluded the survival of immature \textit{X. pallorana} in those plots and it also seems likely that the grass plots did not provide suitable habitat. Although these attempts to augment populations of \textit{C. florus}
were not successful, this endeavor remains worthy of investigation. Design and creation of other, more suitable agroecosystem habitats to augment and/or support alternate hosts of *C. florus* as well as other orchard leafroller parasitoids should be pursued.

The alfalfa cover treatment produced twice the biomass as the grass cover and that biomass contained twice the nitrogen. As such the alfalfa cover treatment had the potential to contribute horticulturally significant quantities of organic matter and nitrogen to the ecosystem. Soil nitrogen level for alfalfa plots, both in the drive and tree rows, were generally higher than in the grass plots. However soil nitrogen levels were rarely excessive for either treatment during the experimental period except for drive rows of alfalfa treatments, in fall of the last two years. These levels did not seem to adversely effect fruit quality or maturity. Seemingly, high fall soil nitrogen levels were mitigated by winter leaching, so that spring levels were consistently low. Only in year-three did tissue analysis indicate excessive nitrogen levels for alfalfa treatment trees but that elevated level was not sustained. Trees in the alfalfa treatment did exhibit darker green leaf coloration, delayed leaf senescence and modestly enhanced terminal and lateral shoot extension indicating a level of invigoration. Overall growth, indicated by truck circumference, was not greater for trees in the alfalfa treatment than for trees in the grass treatment. Likewise, increased tree vigor did not seem to result in increased incidence of physiological disorders or lack of winter hardiness. Soil analysis for other nutrient elements did not indicate any adverse or unusual conditions for or practical differences between either cover treatment. Tissue analysis indicated a typical and generally acceptable overall nutritional status for trees of both treatments for all years with no differences between treatments. Soil organic matter content was not elevated in alfalfa
plots compared to grass plots despite large quantities of biomass produced. It is likely that the sampling depth precluded detection of recently deposited and degraded organic matter in the surface horizon and it will take more time for humus content to increase appreciably in subsurface depths. Soil pH was not affected by cover treatment and remained fairly constant and within an acceptable range throughout the study for both treatments.

Ultimately the alfalfa cover did not adversely affect tree growth or fruit quality in any way. It may be that, over time, an alfalfa cover would contribute excessive quantities of nitrogen to the system and result in excess tree vigor, reduced reproductive growth, and delayed winter acclimation. Finally, the alfalfa cover did not present any particular challenges to orchard operations.

It is important to note that there were many non-significant, equivocal results as indicated by very low power of the test values. It may very well be that the tests were not strong enough to detect differences between cover crop treatments if they existed. This shortcoming arose from having only three treatment replicates. The larger, 0.5 ha plot sizes (instead of more, smaller plots) were a calculated compromise intended to mitigate potential small plot size effect on arthropod community population dynamics and to better approximate an agricultural environment. Interpretation of results must be made in light of this element of experimental design and outcome.
Directions for Future Investigation

From this study several potential and intriguing avenues for research arose. They are as follows:

1. First and foremost, it should be determined if leafroller population homeostasis was achieved or not. If not it would be valuable to determine how long it would take to achieve. It should be determined if the reduced leafroller populations attained will persist at an acceptably low equilibrium level. Similarly, long term population fluctuations, which can be expected, should be quantified and characterized.

2. It would be extremely valuable to replicate this experiment to determine if leafroller population growth and decline would follow a similar pattern and to compare this with a standard insecticide-based leafroller management tactic.

3. The complex of leafroller parasitoids should be definitively characterized.

4. The potential for augmentation and enhancement of tachinids and Braconidae. as early and mid-season leafroller parasitoids is worthy of investigation.

5. The potential of the Pandemis granulovirus and generalist predators for utilization in an integrated leafroller biological control program should be investigated.

6. Other habitat manipulations, instead of or in addition to a simple alfalfa cover may create habitats that support alternate hosts for *C. florus* and other
leafroller parasitoids and should be explored. The inclusion of wild rose on which the strawberry leafroller and *C. florus* overwinter, diversifying the orchard floor cover further and interplanting preferred host plants are examples.

7. Management of codling moth in an environment free of broad-spectrum insecticides will be a challenge. Investigation into an integrated approach that will not disrupt biological control of the breadth of secondary insects and leafrollers is warranted.

8. Assuming that a similar pattern of leafroller population decline with associated levels of crop loss would occur in most orchards, a long-term economic analysis of transitioning to biologically-based leafroller management is also warranted.

9. It was noted that cull apples with leafroller damage often had other damage as well. It would be valuable to investigate whether certain apples were predisposed to leafroller damage and if leafroller damage could be reduced via cultural manipulations such as summer pruning or selective fruit thinning.

10. More sophisticated cullage analysis to determine the extent of leafroller damage and its economic ramifications is called for.

11. Overwintering leafroller larvae trapped in cardboard bands seemed to be indicative of subsequent growing season population densities. It would be
valuable to investigate the potential of using this as a predictive tool and to correlate anticipated leafroller populations to potential economic loss.

12. The long-term effects of alfalfa used as an orchard cover, particularly because of its potential to contribute large quantities of nitrogen to the orchard system, should be evaluated over the long term.
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Appendix A – Plot Map

<table>
<thead>
<tr>
<th>Plot</th>
<th>Total ha.</th>
<th>Core Area ha.</th>
</tr>
</thead>
<tbody>
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<td>.13</td>
</tr>
<tr>
<td>A2</td>
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<td>.13</td>
</tr>
<tr>
<td>A3</td>
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<td>.12</td>
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<tr>
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</tr>
<tr>
<td>G3</td>
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<td>.16</td>
</tr>
</tbody>
</table>

Buffers = minimum of 31.69 m. on common borders
## Appendix B

### Agri-chemical application record

(U.S. measures per applicators records)

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<th>2001</th>
<th>2002</th>
</tr>
</thead>
<tbody>
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<td>Volk oil- 5 gal./acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
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<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
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<td>4/10</td>
<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
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<td>Volks oil- 5 gal. /acre&lt;br&gt; Zinc 50- 6 # /acre&lt;br&gt; Solubor- 3# / acre&lt;br&gt; Rubigan 6 oz./acre&lt;br&gt; (100 gal. /acre applied)</td>
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<td>4/24</td>
<td>Sulfur- 10 # / acre&lt;br&gt; (applied at 100 gal/acre)</td>
<td>Glyophosate- 6 qts. / 100 gal.&lt;br&gt; Spreader- 1 pt./ 100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
<td>Ammonium thiosulfate&lt;br&gt; (ATS)- 1.7 gal. / 100 gal.&lt;br&gt; (applied at 200 gal/acre)</td>
<td>Lime sulfur- 3 gal/ acre&lt;br&gt; Fish oil- 2gal/ acre&lt;br&gt; (applied at 100 gal/ acre)</td>
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<td>5/11</td>
<td>Ammonium Nitrate&lt;br&gt; (34-0-0, granular)&lt;br&gt; 25 # /acre, broadcast</td>
<td>Glyophosate- 6 qts. / 100 gal.&lt;br&gt; Spreader- 1 pt./ 100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
<td>Wetable sulfur- 6 #/acre&lt;br&gt; Rubigan- 6 oz. /acre&lt;br&gt; (applied at 100 gal/acre)</td>
<td>Lime sulfur- 3 gal/ acre&lt;br&gt; Fish oil- 2gal/ acre&lt;br&gt; (applied at 100 gal/ acre)</td>
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<td>5/19</td>
<td>Amid-thin- 1# /100 gal.&lt;br&gt; Sevin XLR- 1pt. /100 gal.&lt;br&gt; Ethrel- 1.5 pt/ 100 gal.&lt;br&gt; Rubigan- 6 oz. /100 gal.&lt;br&gt; Regulaid- 1 pt. / 100 gal.&lt;br&gt; (applied at 100 gal/acre)</td>
<td>Amid-thin- 1# /100 gal.&lt;br&gt; Sevin XLR- 1pt. /100 gal.&lt;br&gt; Ethrel- 1.5 pt/ 100 gal.&lt;br&gt; Regulaid- 1 pt. / 100 gal.&lt;br&gt; (applied at 100 gal/acre)</td>
<td>Glyphosate- 6qts/100 gal.&lt;br&gt; Spreader 90- 1 pt/ 100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
<td>Amid-thin- 16 oz/ 100 gal&lt;br&gt; Ethephon- 1.5 pt/ 100 gal&lt;br&gt; Regulaid-.5 pt/ 100 gal&lt;br&gt; (applied at 100 gal/acre)</td>
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<td>6/2</td>
<td>Sevin XLR- 1 pt. / 100 gal.&lt;br&gt; NAA 200- 1oz. / 100 gal.&lt;br&gt; Regulaid- 1 pt. / 100 gal.&lt;br&gt; (applied at 100 gal/acre)</td>
<td>Sevin XLR-.5 pt. / 100 gal.&lt;br&gt; NAA 200-.5 oz. / 100 gal.&lt;br&gt; Regulaid- 1 pt. / 100 gal.&lt;br&gt; (applied at 200 gal/acre)</td>
<td>Ammonium Nitrate&lt;br&gt; (34-0-0, granular)&lt;br&gt; 50 # /acre, broadcast</td>
<td>NAA 200- 1oz/100 gal&lt;br&gt; Regulaid-.5 pt/ 100 gal&lt;br&gt; (applied at 100 gal/acre)</td>
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<td>6/9</td>
<td>Glyphosate- 6qts/100 gal.&lt;br&gt; Spreader- 1 pt/100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
<td>Glyphosate- 6 qt / 100 gal.&lt;br&gt; Spreader- 1 pt./ 100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
<td>Glyphosate- 6qt/100 gal.&lt;br&gt; Spreader 90- 1 pt/100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
<td>Glyphosate- 6 qt/100 gal&lt;br&gt; Spreader 1 pt/ 100 gal&lt;br&gt; (applied at 25 gal/acre)</td>
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<td>6/29</td>
<td>Gramoxone- 3 pts/ 100 gal&lt;br&gt; Spreader- 1 pt/ 100 gal&lt;br&gt; (applied at 25 gal/acre to young trees only)</td>
<td>Ammonium Nitrate&lt;br&gt; (34-0-0, granular)&lt;br&gt; .034 # N / tree to replant trees only</td>
<td>Glyphosate- 6qts/100 gal.&lt;br&gt; Spreader 90- 1 pt/100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
<td>Ammonium Nitrate&lt;br&gt; (34-0-0, granular)&lt;br&gt; .4 oz/tree&lt;br&gt; hand applied to weak trees only</td>
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<td>7/11</td>
<td>Ammonium Nitrate&lt;br&gt; (34-0-0, granular)&lt;br&gt; .034 # N / tree, to replants only</td>
<td>Glyophosate- 6 qts/ 100 gal.&lt;br&gt; Spreader 90- 1 pt/ 100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
<td>Glyophosphate- 6 qts/100 gal.&lt;br&gt; Spreader 90- 1 pt/100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
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<td>Glyphosphate- 6 qts/100 gal.&lt;br&gt; Spreader 1 pt/ 100 gal&lt;br&gt; (applied at 25 gal/acre)</td>
<td>Glyophosphate- 6 qts/100 gal.&lt;br&gt; Spreader 90- 1 pt/100 gal.&lt;br&gt; (applied at 25 gal/acre)</td>
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<td>8/12</td>
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<td>Glyphosphate- 6 qt/100 gal&lt;br&gt; Spreader 1 pt/ 100 gal&lt;br&gt; (applied at 25 gal/acre)</td>
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APPENDIX C

ATTEMPTS TO AUGMENT THE APPLE LEAFROLLER PARASITOID

**COLPOCLYPEUS FLORUS**

**Introduction**

Leafrollers (Lepidoptera: Tortricidae), both native and imported, have become pests inhabiting commercial apple (*Malus domestica* Borkh) orchards in North America (Weires and Riedle, 1991). In Washington State apple orchards the obliquebanded leafroller, *Choristoneura rosaceana* (Harris) and the, *Pandemis pyrusana* (Kearfoll) leafroller are two most common and destructive leafrollers in pome fruit orchards (Beers et al., 1993; Brunner et al., 2001). Though direct, secondary pests, *P. pyrusana* and obliquebanded leafrollers feed primarily on foliage and do not require fruit to complete their development nor do they seem to particularly seek fruit for feeding. However it is not unusual for larvae to attach leaves to fruit or use fruit clusters as sheltered feeding sites usually resulting in some level of fruit damage (Beers et al., 1993; Brunner, 1991). *P. pyrusana* is, most generally, a pest in established, bearing apple orchards (Brunner and Beers, 1990). The obliquebanded leafroller, a native and widely distributed North American species (Reissig, 1978) is most often (but not exclusively) a pest in newly planted and young orchards in Washington (Brunner and Beers, 1990). Obliquebanded leafroller was described as a prevalent and major pest in British Columbia apple orchards by Madsen (1984a) and Smirle (1993) and it is considered a major apple pest in New York (Onstad et al., 1985). Both leafrollers are polyphagous and have been collected from diverse wild hosts (Brunner and Beers, 1990) however apple and rose have been described as their primary hosts (Mayer and Beirne, 1974a). With the advent of mating disruption for codling moth (*Cydia pomonella*) control and subsequent reduction in broad-spectrum insecticide use, leafrollers have become a
much more serious pest of apple (Beers et al. 1993; Brunner et al. 1994; Warner, 1996a).
Additionally leafrollers are increasingly reported to exhibit resistance as well as cross-resistance
to broad-spectrum insecticides used for their control (Alway 1996b; Carriere et al., 1996; Croft, 1982; Lawson et al., 1997; Madsen and Carty, 1977; Reissig et al., 1986; Vakenti et al., 1984;
leafroller resistance to organophosphates in Washington orchards.

The life histories of *P. pyrusana* and obliquebanded leafrollers are quite similar. In the Pacific
Northwest these species are bivoltine. They overwinter as 1st, 2nd, or 3rd instar larvae.
Overwintering generation larvae become active in the early spring and bore onto opening buds to
feed on expanding leaves and flower clusters. These larvae are fully grown by mid to late May.
Overwintering generation adults usually emerge from late May to early June, with peak activity
in mid-June (Beers et al., 1993). Summer generation egg hatch begins in late August and can
continue through September. The resultant young larvae (1st - 3rd instars) feed on foliage and
fruit for a period and move to build hibernacula in scaffold branches in October (Brunner, 1991).
Knight (2001) reported *P. pyrusana* larval densities to increase five fold between overwintering
and summer generations on apple. Brunner (1997b) offers that leafroller populations tend to
come from within orchard infestations.

Leafroller control in the Pacific Northwest and elsewhere has been and continues to be
accomplished primarily with the use of conventional synthetic broad-spectrum insecticides.
Because obliquebanded and *P. pyrusana* leafroller life cycles are essentially the same, separate
control measures have not been necessary. It is recommended to target the overwintering larvae
just after they have left their hibernacula with a delayed dormant oil/chlorpyriphos treatment. To
avoid disruption of integrated mite management and to minimize resistance development, later
season broad-spectrum insecticide applications are not recommended, however in season azinphosmethyl applications for codling moth have provided significant levels of leafroller control. The bacterial insecticide *Bacillus thuringinesis* (Bt) is often used to control late spring and summer leafroller populations. Brunner (1997b) recommended chlorpyriphos or encapsulated methylparathion treatment of summer generation leafroller when populations exceed 5% shoot infestations. Other management tactics have been explored or are considered to have potential (Anderson and Elliot, 1982; Brunner, 1997a; de Reed et al., 1985; Evenden et al., 1999; Knight and Turner, 1999; Knight et al., 2000; Waldstein and Reissig, 2001; Warner, 1996a; Willson and Trammel, 1980).

Whether from reduced pesticide use, or increased resistance to insecticides, leafrollers in Washington orchards have assumed a key pest status in many Washington orchards (Beers et al., 1993; Knight et al., 1998). In light of the above plus the call for reduced pesticide use and dependence and the development of ecologically based pest management strategies (Benbrook, 1996; Hill, 1999; Lewis et al., 1997; National Research Council, 1996; Wiles et al., 1999) biological control of apple leafrollers is considered an alternative management strategy with potential. (Beers et al., 1993; Brunner, 1996; Pfannensteil et al., 1997).

The chalcidoid wasp *Colpoclypeus florus* Walker (Hymenoptera, Eulophidae) is thought to have great potential as a biological control agent for apple leafrollers in Washington just as it is in Europe (Brunner, 1991; Brunner, 1996; Gruys and Vaal, 1984; Pfannenstiel, 1997; Warner, 1995). In Europe, it has been the subject of a great deal of investigation. It is described by VanVeen et al., (1985) and Milonas and Savopoulou-Soutani (2000) as an oligophagous, gregarious, non-paralyzing ectoparasitoid of Tortricid leafroller species. It has been recorded attacking 32 host species (Dijkstra, 1986; Gruys and Vaal, 1984; VanVeen and Van Wijk, 1987), has a west paleoarctic distribution and is rarely found in natural or semi-natural habitats.
(Dijkstra, 1986). In Europe it is considered to be the most promising parasitic hymenopteran for the control of leafrollers in apple orchards with reduced insecticide input (Evenhuis, 1983). Soenarjo (1979) reported 40 - 90% summer fruit tortrix parasitism levels by *C. florus* in Dutch orchards. Panizza Dalla Monta and Gambro (1973) reported late season parasitism levels by *C. florus* in Italian orchards to have reached 95%.

It is assumed that *C. florus* will demonstrate a similar life history in Eastern Washington as in Europe. There the parasitoids overwinter as mature larvae on a consumed host larvae. Pupation occurs in the spring when orchard leafroller larvae are present. Larger (fourth and fifth instars) host larvae are stung in the head by a female that then remains with the stung larvae inside the webbed, leaf shelter. The stung host spins a dense silken chamber on which the female lays eggs. Eggs hatch and parasitoid larvae locate host larvae and begin external feeding. Host larvae remain alive until feeding of the final *C. florus* instar begins (Beers et al., 1993). The number of parasites that can develop successfully on one host depends upon larval size (Evenhuis, 1974; VanVeen et al., 1985). VanVeen et al. (1985) reported the ability of females (virgin and inseminated) to regulate their clutch size according to larval host size. Two or three hosts are parasitized by an individual female. This low level of parasitism is perhaps in part accounted for by the extremely long time (up to 56 hours in the field) taken to parasitize a single host (Dijkstra, 1986). There appears to be only two generations of *C. florus* per year in Washington as opposed to 4 - 8 generations reported in Europe (Beers et al., 1993; Gruys and Vaal, 1984).

Though *C. florus* is considered the primary parasite of leafrollers in European orchards and to have the greatest potential to afford leafroller biocontrol in integrated pest management programs it is found only sporadically in orchards during the early spring and fall. Parasitism *C. florus* in the summer though, can be high (Brunner, 1996, 1997b; Gruys and Vaal, 1984). The life cycle
of *C. florus*, it seems, is not well synchronized with most orchard leafroller species and few find suitable larval hosts of an advanced (4-5 instar) stage of development for overwintering. Consequently *C. florus* appears to leave the orchard to overwinter on suitable hosts (large, late instar larvae) elsewhere. This results, it is believed, in the scant spring presence and fall/winter absence of *C. florus* in apple orchards (Brunner, 1996; Evenhuis and Vlug, 1983; Gruys and Vaal, 1984). Evenhuis (1974) stated that where *C. florus* is in the spring and early summer is a puzzle. Likewise where and with what host *C. florus* overwinters is also unknown (VanVeen et al., 1985).

*C. florus*, was first reported in Washington by Brunner (1994, 1996). It was introduced to North America from a release of French specimens to control *A. velutiana* in Ontario, Canada. Recovery of *C. florus* from obliquebanded leafroller and *S. ocelluna* in Southern Ontario was reported by Hagely and Barber (1991). It is thought that *C. florus* subsequently became established in British Columbia by the mid-seventies (Brunner, 1996) after its earlier release in Ontario (Hagley and Barber 1991). In north central Washington, Brunner (1996) observed low orchard leafroller parasitism levels (0-13%) during the spring in all test orchards and no *C. florus* was found at that time. However summer leafroller parasitism levels were approximately 75%. Brunner (1997b) also reported up to 98% parasitism by *C. florus* in unsprayed apple orchards in Washington. Other orchards in north central Washington report *C. florus* to be established and providing 50-60% spring leafroller parasitism and 70-80% parasitism in the summer, which suggests a widespread regional distribution (Brunner, 1996).

In Washington *C. florus* may provide another natural enemy to combat orchard leafrollers and the high levels of parasitism noted in unsprayed orchards suggest that *C. florus* is well adapted to the eastern Washington climate. Absence of broad-spectrum insecticides should enhance *C. florus* activity. Brunner et al. (2001) report organophosphate and carbamate pesticides to be
extremely toxic to *C. florus*, and diflubenzuron to completely block reproduction. Other pesticides including pyrethroids, imadclorpid and abamectin also proved toxic. Biorational pesticides such as soap, oil and *B. thuringinesis* caused no toxicity to *C. florus*.

A frequent and main limitation to effective biological control by parasitoids in agroecosystems is the lack of hosts for host alternation and relationships (Stary and Pike, 1999). In this context the utility of *C. florus* as a consistent biological control agent has one distinct limitation. As in Europe, Washington orchard leafroller species are not appropriate overwintering hosts for *C. florus*, which requires large (4 - 5 instar) larvae (Brunner, 1996). *C. florus* therefore may not occur in Washington orchards in sufficient numbers to economically control *P. pyrusana* and oblique-banded leafrollers in the spring because of low endemic overwintering populations (Brunner, 1996). Future success with *C. florus* as a leafroller biocontrol agent may depend upon the identification and utilization of an appropriate alternate and overwintering host(s) to augment host alternation and in-orchard overwintering of *C. florus* (Alway, 1997a; Pfannenstiel, 1997).

In Washington the strawberry leafroller, *Ancylis comptana fragaria* has been found to be a naturally occurring alternate host for *C. florus*. The strawberry leafroller inhabits wild rose (*Rosa woodsii*) patches near apple orchards (J. Brunner, 2001). As such it may be that this native leafroller species could be effectively utilized as an in-orchard, alternate host and augment the presence and activity of *C. florus* as a season-long biological control agent. Likewise the alfalfa leafroller, *Xenotemna pallorana*, a native pest of alfalfa in Washington, has been identified as a suitable host for *C. florus* (Nobbs, 1977). According to Chapman and Lienk (1971) legumes are the primary hosts of *X. pallorana* and tree fruit crops are likely secondary hosts used to complete its life cycle only when preferred hosts (legumes) are unavailable. Because *X. pallorana* will not preferentially feed on fruit trees and has a similar life cycle as fruit tree leafrollers but overwinters as a mature larvae it could also prove to be a suitable, in orchard, over-
wintering/alternate host for the leafroller parasitoid \textit{C. florus}, increasing its springtime presence in the orchard and efficacy as an early season apple leafroller biocontrol agent (Brunner, 1997; Nobbs, 1977).

Thus it seems feasible that augmentation \textit{C. florus} populations to affect increased apple leafroller parasitism may be accomplished via utilization of \textit{A. comptana fragaria} and/or \textit{X. pallorana} as alternate/overwintering hosts of \textit{C. florus} particularly in an orchard environment were broad spectrum insecticide use is curtailed and \textit{C. florus} conserved. Augmentation involves activities that are designed to increase the numbers or effect of existing natural enemies. This is commonly achieved by releasing additional natural enemies into the system or by modifying the environment to promote greater numbers and/or effectiveness of natural enemies (Beers et al., 1993; DeBach, 1964; Flint and van den Bosch, 1981; Mills, 1992; Pedigo, 2002; Stary and Pike, 1999). Conservation entails environmental modification to reduce adverse, population reducing effects on parasitoids such as elimination of a toxic pesticide (Flint and van den Bosch, 1981; Pedigo, 2002).

Augmentative releases are expected to result in temporary suppression only as opposed to significantly changing the pest equilibrium level. As such they are thought of as “biotic insecticides” (Johnson and Wilson, 1995; Pedigo, 2002). Though arthropod natural enemies have been used successfully in inundative releases (Oatman and Platner, 1971; Oatman and Platner, 1978, Oatman et al., 1977) many other attempts have not been successful. Lack of success is generally attributed to insufficient coverage of the area affected by the pest or to environments not supportive of the numbers released (Pedigo, 2002). Conversely, in inoculative releases, it is the progeny of the released natural enemies that are expected to have the greatest impact on pest populations. Environmental manipulations are also used to augment or conserve natural enemy populations and activity (Norlund, 1984). This strategy generally involves
utilizing the crop or surrounding vegetation as a field insectary to increase natural enemy
numbers or make them more efficient. Examples are common and include providing sources of
alternate, supplementary or complimentary herbaceous or animal foods, enhancing refugia,
nesting sites, overwintering sites, and modifying climates (Flint and van den Bosch, 1981;
Norlund, 1985; Pedigo, 2002, Bugg and Picket, 1998). Cover crops in orchards have been and
are currently used for such purposes and investigations into such ensue (Altieri, 1994; Altieri and
Nickolls, 1999; Bugg and Waddington, 1994; Nickolls and Altieri, 2001; Wyss, 1995).
Leguminous plants, such as alfalfa, are often considered for orchard cover and habitat
diversification (Altieri, 1994; Brown and Scmitt, 1996; Rice et al., 1998; Smith et al., 1994).
They are recognized as “stabilizing crops” used to improve soils and crop yields and to increase
diversity of beneficials (Stary and Pike, 1999).

It may be that the combined effect of eliminating broad-spectrum insecticide use, coupled with
habitat manipulation in the form of an alfalfa cover may support *X. pallorana* populations to
serve as an alternate host and enhance the level of springtime leafroller biological control in
Washington apple orchards. Likewise it may be possible to use parasitized populations *A.
comptana fragaria* in augmentative releases of *C. florus* to facilitate enhanced orchard leafroller
biological control. To that end the objectives of this study were to:

1. Evaluate the efficacy of seeding an orchard, cultivated with either grass or alfalfa
cover and no in-season insecticide applications, with *C. florus*-parasitized strawberry
leafrollers to augment the biological control of apple leafrollers by *C. florus*.

2. Attempt to establish *X. pallorana*, to serve as an alternate/overwintering host for *C.
florus* in an orchard cultivated with either grass or alfalfa cover and no in-season
insecticide applications.
Materials and Methods

My attempt to establishment *X. pallorana* as an alternate/overwintering host for the parasitoid *C. florus* was conducted during the growing season of 2000 and the attempt to augment *C. florus* in the orchard by seeding *C. florus* parasitized strawberry leafrollers was done in 2001. Plots for this experiment were established in a 3.12-hectare, 5th leaf, mature-bearing Fuji (BC 2/ M9) apple block in north central Washington. It was in proximity to many commercial apple, cherry and pear orchards. Trees in the block were planted at a spacing of 1.2m X 3.96m for an approximate density of 1,977 trees per hectare. They were trained to a modified HYTEC system typified by a central axis, conical shape and aggressive lateral renewal (Barritt, 1992) and supported on an upright, 3-wire, 3m high, trellis. Portions of the experimental block bordered apple orchard, sweet cherry orchard and wild vegetation.

The 3.12- hectare block was divided into six contiguous plots varying in area from 0.49 to 0.57 hectare and containing from 1004 to 1056 trees each. Plots were configured to minimize borders with adjacent plots. A randomized block design was utilized for this experiment (Davis, 2000; Snedecor and Cochran, 1976). The three treatments each of alfalfa or grass covers were equally and randomly assigned to one of the six, approximately 0.5 hectare, plots so that there was three replications of the grass cover treatment, designated plots G1, G2, and G3, and three replications of the alfalfa cover treatment, designated plots A1, A2, and A3 (see Appendix A). Thus there were three replicate blocks; each containing two experimental cover treatment plots. For the *C. florus* parasitized *A. comptana fragaria* seeding attempt, one alfalfa plot (designated A1- control) and one grass plot (designated G1- control) were utilized as control plots. The remaining four plots received experimental treatment.
Both alfalfa and grass plots were sown with their respective cover cultivar on May 21 of 1999 and in 2000 and 2001 stands were quite homogenous. A standard grass orchard cover mix of perennial rye and red fescue was utilized for the grass cover treatment while 'Vernal', an older, drought tolerant, lower vigor cultivar, was utilized for the alfalfa cover treatment. A 1.52m wide, tree row, weed-free strip was maintained with glyphosate herbicide per standard orchard management practice. The orchard block was farmed utilizing standard practices with the exception of arthropod pest management. All plots were uniformly cultivated. Mating disruption was used for codling moth (Cydia pomonella) management. Isomate-C pheromone emitters were dispensed in the treatment plots at 500 emitters per hectare per standard recommendations and practice. This was considered a low or half emitter rate. Other than a single, delayed dormant superior oil application (at 11.3 liters/378 liters of water) no insecticide treatments were utilized in the plots for arthropod management during growing seasons.

**Alfalfa leafroller (X. pallorana) establishment and parasitism:**

Beginning in late June and through mid-October (2001), I set out ten, third instar, sentinel X. pallorana larvae in five, 1-meter square areas per plot on a weekly basis. Fifty sentinel larvae were set out per plot per week (450 per plot and 1350 per treatment) during the experimental period. Larvae used for this purpose were raised at the Washington State University – Tree Fruit Research and Extension Center, Wenatchee, Washington on a modified pinto bean-based diet for noctuids (24± 2° C, 16:8 (LD) photoperiod). Specimens to initiate the colony were collected from alfalfa near Quincy, Washington (Nobbs, 1997). The release sites were flagged for identification. Seven days after release sentinel X. pallorana larvae collections from release sites were attempted. Collected larvae were brought to the lab and reared out. Parasitism rates and parasitoid species were recorded. During July of 2000, 18 X. pallorana field-release cages (bottomless) were constructed of PVC and fiberglass netting. Three cages per plot were placed
in selected plot rows and seeded with male and female *X. pallorana* adult moths (5 female and 5 male per cage). Cages were moved to a new location weekly and introduction of *X. pallorana* repeated. Starting mid-August and continuing through mid-September, weekly visual-timed inspections of the cover were conducted in seeded rows to determine the presence/absence of *X. pallorana* egg masses that might be present as a result of adult *X. pallorana* seeding. I searched each plot for 15-minute periods looking for egg masses every 5 days. The number of egg masses found per plot was recorded. Finally we attempted to trap adult male *X. pallorana* for further indication of their establishment in the orchard. Adult female *X. pallorana* were placed within a length of cardboard tubing that was capped at each end with nylon screen. The female-containing tubes were suspended in a sticky bottomed wing trap. The traps were hung mid-height in the tree canopies. One trap per plot was utilized. Adult male *X. pallorana* catch was recorded weekly.

*C. florus* parasitized strawberry leafroller (*Ancylis comptana fragaria*) introduction and *P. pyrusana* parasitism:

*A. comptana fragaria* larvae (in retreats) were collected in the spring from a wild, native rose (*Rosa woodseii*) patch in North Central Washington. The collected larvae were then introduced to potted strawberry (*Fragaria* sp.) plants (cv. Quinolt) in a greenhouse by placing rolled rose leaves (*A. comptana fragaria* retreats) on the strawberry plants. After the larvae produced retreats (evidenced by rolled leaves and webbing; generally within 24-48 hours) on the strawberry plants I then, with the strawberry plants under a netted cage, introduced approximately 100 *C. florus* adults to a group of 12 strawberry plants. The number of *A. comptana fragaria* and *C. florus* utilized per dozen pots varied per the availability of each species. The *C. florus* were allowed to parasitize the strawberry leafrollers on the strawberry
plants for 10 days. After the 10 day period the potted plants with *C. florus*-parasitized *A. comptana fragaria* larvae where set out in groups of three pots at three randomly selected sites in each plot and left for 10 days. After that time they were removed and replaced with new pots of strawberry plants infested with *C. florus*-parasitized strawberry leafrollers.

Potential per pot *C. florus* emergence was estimated by harvesting one rolled leaf per potted strawberry plant, placing it in a covered Petri dish and counting the number of adult parasitoids to emerge. The number of *C. florus* adults, that emerged from each retreat was multiplied by the number of retreats on corresponding potted strawberry plants. When set out in the orchard plots, the pots were sunk into the ground to minimize pot soil and strawberry plant desiccation.

Starting in early June and through mid-October of 2001, five *P. pyrusana* larvae were collected every 10 days from each of 30 flagged trees in each plot. The flagged trees radiated from the point of potted strawberry plant placement. If flagged trees lacked *P. pyrusana* larvae then collection was made from adjacent trees. Collected larvae were returned to the laboratory to be reared out. Parasitism rates and parasitoid species were recorded.

**Results and Discussion**

**Alfalfa leafroller (*X. pallorana*) establishment and parasitism:**

A total of 36 *X. pallorana* egg masses were found during the first inspection in mid-August with 22 egg masses found on alfalfa leaves in the alfalfa plots and 14 egg masses found on clover or dandelion leaves in the grass plots. No egg masses were ever found on grass blades indicating that grass is not a suitable host for *X. pallorana* and that broadleaved plants are preferred.

Weekly inspections continued through mid-September, however only 4 egg masses were found after the initial observation. Three of those egg masses were in alfalfa plots and one in a grass
plot (on clover). Because of the lack of any significant level of success, this strategy was not continued. In the absence of broad-spectrum insecticides, generalist predators likely proliferated in the cover and may have fed upon *X. pallorana* eggs and larvae. We therefore attempted to ascertain and characterize cover crop arthropod communities by conducting two spring-time (May, 2001) sweep net samplings. Overall there were considerably greater numbers of insects in alfalfa than in grass. The average yield of insects per 30 sweeps was 344.1 in alfalfa compared to 38.6 in grass. For both treatments pest species outnumbered beneficial species. In alfalfa there were 297.5 pests vs. 46.6 beneficials per plot sample (30 sweeps), a 6:1 ratio of pest to beneficial insects. The predominant pest species were pea aphid, *Acyrthosiphon pisum* (Harris) (221.0/ plot), leafhopper, *Typhlocyba pomaria* McAtee (55.6/ plot) and lygus bug, *Lygus lineolaris* (Palisot de Beauvois) (11.3/ plot). The dominant beneficial species were lacewings (7.0/ plot), big-eyed bug (9.7/ plot), damsel bug (3.3/ plot), ladybird beetle (4.0/ plot), aphidid wasp (12.7/ plot), chalcidoid wasp (1.3/ plot) and ichneumonid wasp (7.3/ plot). In grass there were 35.3 pests vs. 3.3 beneficials per plot sample (30 sweeps); an 11:1 ratio of pest to beneficial insects. The predominant pest species were leafhoppers (27.3/ plot) and lygus bug (0.7/ plot). The dominant beneficial species were lacewings (0.3/ plot), big-eyed bug (1.3/ plot), damsel bug (0.7/ plot) and lady beetle (1/ plot). Notably there were no parasitoid wasps retrieved from grass plots. Ground dwelling generalist predators that are not typically trapped by sweep netting, such as predaceous ground beetles (Carabidae), and which we suspect may have contributed to *X. pallorana* mortality, were not assessed. On the one hand it would seem that grass plots, with far fewer generalist predators, might have allowed greater numbers of *X. pallorana* to persist than in alfalfa plots. However because *X. pallorana* only established on sparse dandelion and clover plants, suitable habitat may have been insufficient and they may have simply not occurred in great number in the first place. On the other hand being located on dandelion and clover may have resulted in the larvae being more apparent to predators. Similarly the relative paucity of
prey in the grass plots may have rendered them subject to high levels of predation. Conversely the abundance of prey in alfalfa (e.g. pea aphid) likely satisfied predator need to a substantial extent allowing *X. pallorana* larvae to escape.

Another possibility is that the laboratory-reared adult *X. pallorana* were not sufficiently acclimated, were too delicate for the release process or were otherwise not reproductively fit. In any case our attempt to establish the alfalfa leafroller in the orchard cover was unsuccessful and it seemed highly unlikely that it could be easily accomplished. Few *X. pallorana* males were captured in pheremone traps further indicating lack of establishment. For each cover treatment a season-total of nine male moths were caught. The largest single catches, 5 in alfalfa plots and 7 in grass plots, were recorded for August 22. On other dates one or two moths may have been caught but usually the traps were empty. It appears that the traps were functioning and if higher densities of *X. pallorana* were present more would have been caught. As such, though *X. pallorana* was an adequate and promising alternate host under laboratory conditions, our inability to establish it in the cover crop rendered this strategy of minimal or questionable potential.

Sentinel *X. pallorana* larvae were also set out and collected on a scheduled basis from the latter part of June through the first week of August (2001) to assess potential for it to serve as an alternate host for the parasitoid *C. florus*. In all, 1350 sentinel larvae were set out for each cover treatment during the course of the study. Far fewer were retrieved. In alfalfa only 120 sentinels were recovered (8.9% recovery rate) and in grass 75 were recovered (5.6% recovery rate). The largest alfalfa retrievals occurred in June and early July for alfalfa plots but in August for grass plots. Several reasons for low retrieval rates are proposed. Sentinel larvae may have widely dispersed upon release making their subsequent detection and retrieval difficult. They may have
not been sufficiently hardy and may have succumbed to a harsh environment. Or it may have been that they too ended up as prey for generalist predators in the insecticide-free environment. Regardless, parasitism rates were extremely low. In alfalfa only 9 of 120 (7.5%) retrieved sentinel *X. pallorana* larvae were parasitized over the entire season. Eight sentinels out of 75 (10.7%) retrieved from grass plots were parasitized. Of all the parasitoids reared from retrieved sentinel *X. pallorana*, none were *C. florus*. Tachinids and Braconidae were exclusively reared from the retrieved larvae, from both treatments throughout the season with the exception of one unidentified hymenopteran reared from a late July collection. Interestingly, the single highest parasitism rate of 100% (6 of 6 for grass and 4 of 4 for alfalfa) for both cover treatments was recorded for the last sentinel set retrieved on September 29. It would seem that, in the orchard, *X. pallorana* may not readily be sought after or detected by apple leafroller parasitoids, including *C. florus*, and as such will not serve as an alternate host.

**Parasitized strawberry leafroller** (*Ancylis comptana fragaria*)

**Introduction and *P. pyrusana* parasitism**

For all treatments, including the controls (no pots set out), fairly high seasonal rates of parasitism were detected (Table C.1). Overall parasitism for *P. pyrusana* collected in the control alfalfa plot was 68.5%, control grass 55.6%, alfalfa treatment 69.5% and grass 73.8%. The prevalent parasitoid reared from *P. pyrusana* larvae was not *C. florus* but overwhelmingly Braconidae. For the alfalfa control plot 97.1% of reared parasitoids were Braconidae and for the grass control plot 82.5% were Braconidae. No *C. florus* were reared from control plot *P. pyrusana*.
Table C.1. Season-long *P. pyrusana* percent parasitism rate in *C. florus* parasitized *Ancylis comptana fragaria* seeded alfalfa and grass cover crop plots.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Mean</th>
<th>n</th>
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<tbody>
<tr>
<td>alfalfa-seeded</td>
<td>69.47</td>
<td>91</td>
</tr>
<tr>
<td>grass-seeded</td>
<td>68.46</td>
<td>89</td>
</tr>
<tr>
<td>alfalfa-control</td>
<td>64.81</td>
<td>34</td>
</tr>
<tr>
<td>grass-control</td>
<td>55.56</td>
<td>40</td>
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Mean were transformed for analysis, those followed by the same letter are not significantly different (\(P = 0.05\)). See F values cited in the text.
larvae; tachinids accounted for the balance of parasitoids reared. For the alfalfa plots seeded with *C. florus*-parasitized strawberry leafrollers, 69.5% of *P. pyrusana* larvae were parasitized, but again 95.6% of parasitoids reared were Braconidae. Two (4.6%) parasitized larvae yielded *C. florus*. Larvae from *C. florus*-seeded grass plots exhibited a 68.5% parasitism rate. Again the preponderance of parasitoids reared was Braconidae (85.4%). Only one *C. florus* was reared (1.6% of total parasitism) with the balance being tachinids (13.5%). There were no significant differences in parasitism rate between grass cover plots, alfalfa cover plots or the alfalfa control plot. The grass control plot had a significantly lower parasitism rate than the other plots (*F* = 20.49; *DF* = 3,8; *P* < 0.001). Only the *C. florus*-seeded plots yielded *C. florus* though their numbers were not great enough to indicate any level of success. Again alfalfa plot *C. florus* parasitism was 4.6% of overall parasitism while in grass plots *C. florus* contributed 1.6% to total parasitism (Table C.2). It is worth noting that all alfalfa plots (including control alfalfa) yielded over 4 times fewer tachinids than did grass plots (including control grass) while the number of Braconidae retrieved were consistently high for all plots. The preponderance of Braconidae were retrieved from larvae collected prior to August 27. No tachinids were retrieved after August 27 while all 3 of the *C. florus* retrieved were from larvae collected on August 27 (one *C. florus*) or thereafter (two *C. florus*).

Potential per pot *C. florus* yield (from parasitized *A. comptana fragaria* on the strawberry plants) was estimated for one batch of plants. Estimated *C. florus* emergence per pot ranged from 36 to 120 parasitoids, with an average of 64.9 parasitoids per pot. It may very well be that *C. florus* was
Table C.2. Percent of overall *P. pyrusana* parasitism by *C. florus* in *C. florus* seeded alfalfa and grass cover plots

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<table>
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<tbody>
<tr>
<td><strong>alfalfa- seeded</strong></td>
<td>4.68 ; n= 2</td>
</tr>
<tr>
<td><strong>grass- seeded</strong></td>
<td>1.66 ; n= 1</td>
</tr>
<tr>
<td><strong>alfalfa- control</strong></td>
<td>0.00</td>
</tr>
<tr>
<td><strong>grass- control</strong></td>
<td>0.00</td>
</tr>
</tbody>
</table>
not introduced in sufficiently large enough numbers to appreciably or effectively augment native
*C. florus* and enhance biocontrol of *P. pyrusana* leafrollers by that parasitoid.

**Conclusion**

It would appear that the introduction of strawberry plants infested with *C. florus*-parasitized
strawberry leafrollers made no real difference in rates of orchard leafroller parasitism by *C. florus*. Overall parasitism rates ranged between 55.6% and 69.5% for the sampling period of August 4 through October 3. There were no practical differences in parasitism rates between the cover treatments and the designated control plots (one grass and one alfalfa). For practical purposes the attempt to augment *C. florus* was wholly unsuccessful. Almost no *C. florus* were reared from *P. pyrusana* larvae collected in the proximity of augmentation; two were obtained from alfalfa and one from grass. The vast preponderance of parasitism was by Braconidae.

However, I was unable to start augmentation until relatively late in the season (end of July) due to an inability to obtain *C. florus* for *A. comptana fragaria* parasitization. It may be that if augmentation started earlier results would have been different. As the season progressed it became increasingly difficult to find *P. pyrusana* larvae and collected numbers decreased substantially. For example, for early August, 17 to 35 larvae per plot were collected for rearing but by mid-September we were able to find only a few and by October almost none. It is interesting to note that, fairly consistently, as the number of larvae collected declined the rate of parasitism increased. This however may be an artifact of the parasitized larvae being more apparent to the sampling activity while un-parasitized larvae escaped detection. This would result in an over estimation of parasitism. The highest retrieval rates (19 to 35 larvae) yielded the lowest parasitism rates (31% to 50%). When larvae collection numbers declined to about 8 to 18 then parasitism rates increased to about 78% to 85% and when collections were but 2 to 7
larvae parasitism was often 100%. This trend indicates the significance of sampling timing relative to parasitism rate estimation. Additionally it seems apparent that establishment of *X. pallorana* as an alternate host for apple leafroller parasitoids is not a practical consideration. Likewise it seems that even if they could be established that, in the field, apple leafroller parasitoids do not readily seek or utilize them as hosts. Should apple leafroller populations differ from those in the experimental plots, which were relatively high, that could change.