# IMPACTS OF STRIP CULTIVATION IN APPLE AND GRAPE SYSTEMS

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ABSTRACT

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Strip cultivation is a ground management tactic available to perennial fruit growers that provides a non-chemical means of weed control. I compared strip cultivation to herbicide application in an apple orchard and a vineyard over two years, measuring impacts on weed cover, soil nitrogen, leaf nitrogen, soil organic matter, ground predator communities, and two pest insects: the plum curculio and codling moth. Weed cover decreased more quickly after cultivation events than herbicide events, and was less spatially variable in cultivated plots. Soil and crop nitrogen conditions were similar between the treatments, except for N mineralization occurring in the soil 2-4 weeks after each cultivation event. No differences in soil organic matter content were observed. Differences in ground predator community varied between taxa, and prey removal experiments indicated very similar predator activity between the two treatments. The cultivator buried fifty percent or more of sentinel pest insect larvae on the soil surface. A greater proportion of plum curculio larvae buried under laboratory conditions survived to adulthood compared to unburied larvae. Buried codling moth adults were unable to emerge from burial. Buried codling moth larvae had drastically reduced survival to adulthood compared to unburied larvae.

This thesis is dedicated to all people working to maintain their livelihood while taking care of that which we are borrowing from future generations, and to the memory of Harold Nichols.

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# CHAPTER ONE: REVIEW OF THE RELEVANT LITERATURE

Floor management is an essential component of perennial fruit production. Reduction of weed pressure is necessary in order to reduce competition with the crop for nutrients and water (Hogue and Neilsen 1987, Guerra and Steenworth 2012). These in turn affect vegetative growth, tree or vine development, yield, and fruit quality (Mullins et al. 1992, Neilsen and Neilsen 2003). Weed management strategies also have an impact on habitat for insect pests and insect natural enemies by determining the food resources available in the vegetation, habitat complexity, and sheltering or overwintering sites (Pedigo 1989). Ground management also can alter the amount of organic matter and the density of the soil - both of which determine water- and nutrient-holding capacity (Stevenson and Cole 1999, Oliviera and Merwin 2001).

This research focuses on apples (Rosaceae: *Malus domestica* L.) and grapes (Vitaceae: *Vitis* spp.). A lack of effective weed management in apple results in water and nutrient uptake by ground vegetation, reducing that available to the tree and its crop (Bedford and Pickering 1914). Competition from ground vegetation can greatly reduce N uptake by vines (Hanson and Howell 1995). Water availability to grape vines can also be reduced by the presence of common weeds, such as *Malva neglecta* Wallroth (common mallow) and *Taraxacum officinale* Wigg (dandelion), both of which have higher transpiration rates than grape vines (Lopes et al. 2004).

Both crops have a diversity of insect pests (Slingerland and Crosby 1914). Any cultural technique that can increase the population or activity of natural enemies of these pests can play a role in protecting the crop (Hajek 2004, Pedigo 1989). Habitat management has been shown to have a significant influence on the damage done by pest insects in perennial fruit (Landis et al. 2000, Fiedler et al. 2008). Such changes have a greater impact on farms using low levels of insecticides, or under organic management (Crowder et al. 2010).

## Common Tools for Ground Management

My thesis is primarily concerned with the consequences of using strip cultivation as a ground management strategy in comparison with the more commonly used herbicide strip tactic. Thus, the following floor management strategies are discussed below: herbicide strip, grazing, mulch, in-row cover cropping, flame weeding, and strip cultivation, in that order. The herbicide strip is the most commonly used tool for floor management. However, those growers interested in reducing or eliminating the use of herbicides, including certified organic growers, are exploring other techniques of weed management (Granatstein and Sanchez 2009).

### Herbicides

Typical perennial crop floor management consists of maintenance of a mowed grass alleyway between rows with an herbicide strip within the tree- or vine-rows. This has been the case since broad-spectrum herbicides became available in the 1950's (Hogue and Neilsen 1987). The grass alleyway prevents compaction and rutting on tractor passes, while the vegetation-free herbicide strip reduces competition faced by trees and vines for water and nutrients. This approach ensures little to no competition with the crop for fertilizer application, but also results in a lack of retention of mineral fertilizers due to increased risk of leaching (Sanchez et al. 2003) and has been shown to result in the rapid loss of soil organic matter (Hipps and Samuelson 1991). The herbicide strip is also versatile as a means of weed control over a wide variety of environments. Limited herbicides are available for use in organic orchards. Several that have been tested, including *Brassica* seed oil and clove oil, have been found ineffective at controlling weeds (Hoagland et al. 2008).

In a number of ground management trials, herbicide strip treatments have shown the highest yield and vegetative growth, due to the complete removal of competition from weeds (Van Huyssteen and Weber 1980, Hogue and Nielsen 1987, Merwin and Stiles 1994). Decreases in soil porosity and organic matter have been observed in herbicide strips (Atkinson and Herbert 1979). In a 14-year orchard study in Great Britain, Hipps and Samuelson (1991) observed a loss of both total nitrogen (N) and organic matter from the soil.

Injury to first- or second- year crop plants is common from broad-spectrum herbicides such as paraquat (1,1'-dimethyl-4,4'-bipyridinium ion) and glyphosate (N-phosphono-methyl-glycine) (Dami et al. 2005). Many crop plants, including glyphosate-resistant varieties, have been shown to be more susceptible to disease organisms at recommended levels of glyphosate application (Johal and Huber 2009). The evidence is still unclear on the direct impact of herbicides on soil fungi and bacteria (Carlisle and Trevors 1988, Busse et al. 2001). That said, an herbicide strip will necessarily reduce soil biotic activity over time because, in a completely vegetation-free zone like that created by herbicides, there will be fewer inputs of microbial food to the soil (Bardgett 2005). Some herbicides persist in the soil for extended periods, competing with inorganic phosphate for soil binding sites (Schuette 1998).

**Grazing**

Livestock grazing was one of the original methods of ground management in orchards (Merwin 2003). Ranging hogs and chickens was the norm in orchards before clean cultivation became common (Dolan 2009). Hog grazing is used in some modern apple orchards to reduce both weed and insect pressure (Nunn et al. 2007). Hogs are an effective way to remove dropped fruit containing larvae of pest insects including the Plum Curculio, *Conotrachelus nenuphar* (Coleoptera: Curculionidae) Herbst (Buehrer unpublished). Geese ranged in moveable coops and chickens at high densities can also be a successful ground management strategy in orchards (Clark at al. 1995). Grazing animals also results in addition of organic N, which mineralizes at variable rates depending on the livestock species (Kirchmann 1991). However animal integration is not a common floor management tactic for several reasons: specialization in the grower community and regulatory structure; Good Agricultural Practices (GAP) standards; high cost for any growers not already running a livestock operation; complexity of ranging livestock in an area where pesticides will be sprayed; and the difficulty of incorporating dwarfing and semi-dwarfing rootstocks with grazing or browsing livestock (Hilimire 2011, Jackson et al. 2011).

**Mulching**

Mulching is the practice of laying down material over the surface of the rows to smother weeds. These materials may be organic in nature —*e.g.* wood chips, pine bark, straw, etc.; or they may be artificial, such as black plastic or geotextiles. Organic mulches add soil organic matter and retainable nutrients (Hogue and Neilsen 1987). Black plastic mulches reduce weed competition, soil moisture retention, and soil temperature (Hogue and Neilsen 1987). In an organic Pinot Noir vineyard in New York undergoing ground management trials, yields were much higher in the geotextile treatment after only two years without altering anthocyanin content, Brix level, or ripening time (Hostetler et al. 2007). Unfortunately mulch also provides habitat for rodents, which can damage or kill young trees and vines (Merwin and Stiles 1994).

Organic mulches are an effective way to add nutrients to the soil that will be retained (Walsh et al. 1996), however they present a more complex nutrient input strategy than inorganic fertilizers. When they have a high surface area and high C:N ratio, the process of their digestion by microorganisms temporarily causes N immobilization (Haynes 1980). Conversely, mulching can also cause unwanted late-season mineralization of N, depending on the material used (Granatstein and Mullinix 2009, Zoppolo et al. 2011). Lower surface area mulches such as wood chips, however, do not cause N immobilization after they are applied; "exceptional" growth of young plantings is observed under wood chip mulches (Hoagland et al. 2008). Some growers have found that occasional mulching can be an effective way to add nutrients and organic matter, and reduce weed competition in the year in which it is done. For others, mulching is not considered practical as a primary weed management strategy because of the large amount of materials needed, as well as labor to distribute mulch around the crop (Guerra and Steenwerth 2012).

**Cover crops**

Some fruit growers utilize cover cropping for floor management. They commonly plant low C:N ratio cover such as clover, alfalfa, vetch, or orchard grasses. Cover consisting of grass can compete with the crop for N: measurements of leaf nutrients have shown lower N content and higher contents of other minerals in apples growing in grass-covered rows (Haynes 1980). This difference has been shown to decrease fruit weight and increase fruit quality parameters in apples (Merwin 2003). For the same reason, cover crops in wine grapes are an effective way to decrease the N and water available to vines late in the season, which reduces unwanted vegetative growth and improves grape quality, often without reducing yield (Wheeler et al. 2005).

Cover crops reduce nitrate leaching, which is of concern for water quality (Sanchez et al. 2003), and they tie up mineral N during the season's growth (Merwin et al. 1994). Mineralization of N occurs when cover crops, particularly legumes, are tilled in (Haynes et al. 1986). For these reasons, cover crops can be used as a nutrient "savings account" which are released after mowing or tillage, depending on whether one is using perennial or re-seeding annual cover

(Granatstein and Sanchez 2009, Guerra and Steenwerth 2012). Cover cropping is also an effective way to prevent soil erosion in sloped orchards and vineyards (Klik et al. 1998).

**Flaming**

Flame weeding is the process of applying heat to weeds to kill them, usually via a propane flame weeder. Depending on the maturity of the weeds, the flame is either used to desiccate them by a brief pass-over, or burn them directly - achieving correct lateral speed of flamer movement over the row does take some skill (Merfield 2002). In an organic apple ground floor management study conducted by Zoppolo et al. (2011), C and N pools were not impacted by flame burning. Flame weeding presents several risks - injury to workers, damage to irrigation, and drawbacks - increase greenhouse gas pollution due to fossil-fuel burning, and necessity of more frequent treatment than herbicides (Stefanelli et al. 2009, Guerra and Steenwerth 2012). Further, flame weeding selects for survival of perennial weeds and grasses over annual broadleaf cover (Ferrero et al. 1994). Much less research has been done with flame weeding compared to other ground management treatments, but it appears to have a similar effect as that of post emergent herbicides for removal of competition.

**Cultivation**

After hog or chicken grazing became less common, and before herbicides were widely available, clean cultivation of orchards and vineyards was the norm, where the entire orchard or vineyard soil surface was kept weed-free using a cultivating implement (Figure 3) (Hogue and Neilsen 1987). Strip cultivation, in contrast, is a floor management strategy in which drive rows are kept in mowed sod, and a vegetation-free strip is maintained on each side of the tree- or vine-rows using an offset cultivator (Weibel 2002). After the ground vegetation begins to recover, another pass is made to till it under. In a Midwestern U.S. context, three to five passes are usually necessary to keep weeds from seeding; a single early-season pass is generally insufficient (Moran and Ricker 2003). Two versions of this technique are as follows: 1. In the Swiss Sandwich System (Figure 1), a narrow strip in the tree- or vine-rows is left untilled and native vegetation is allowed to grow freely (Weibel 2002). e.g. with a notch disc tiller, tooth arrow tiller, or spider tines implement (Figure 4, Matthew Grieshop). 2. In-Row Strip Tillage (Figure 2) refers to a system wherein the whole in-row area is cultivated. In-Row Strip Tillage necessitates an implement capable of lateral movement with respect to the tractor, such as a Weed Badger® (Weed Badger, Marion, ND) or Radius Hoe® (Clemens Vineyard Equipment, Inc., Wittlich, Germany) (Figures 5 and 6, Marilyn Kennel).

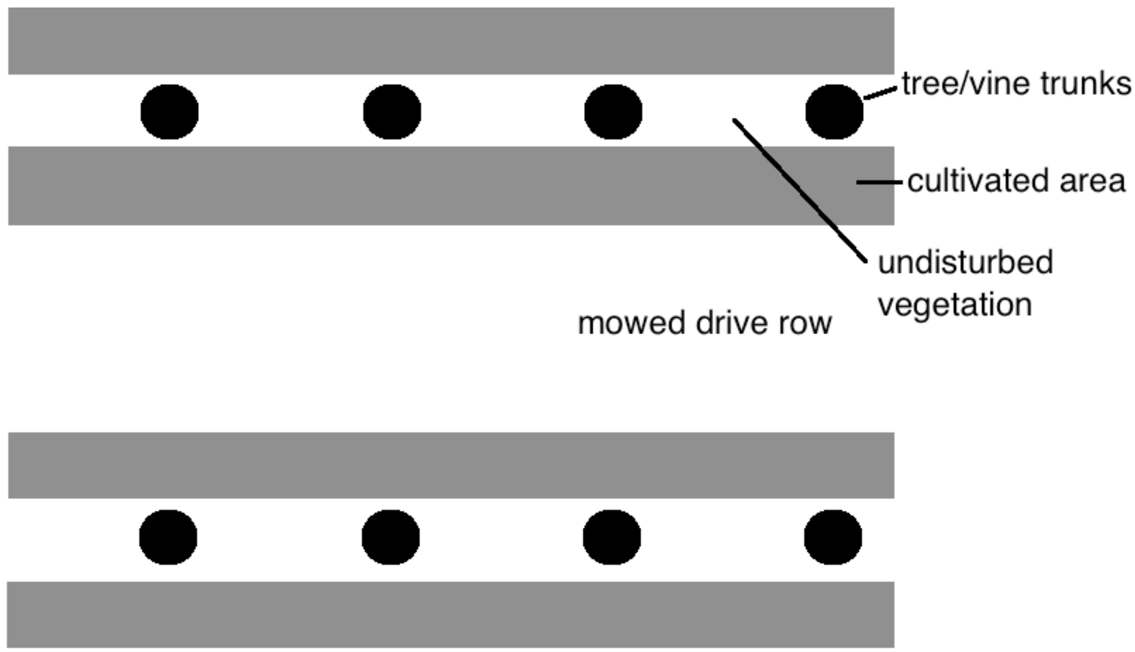


**Figure 1. Sketch of the Swiss sandwich system**. Overhead view, with black circles denoting tree or vine trunks, and grey area denoting cultivated area.

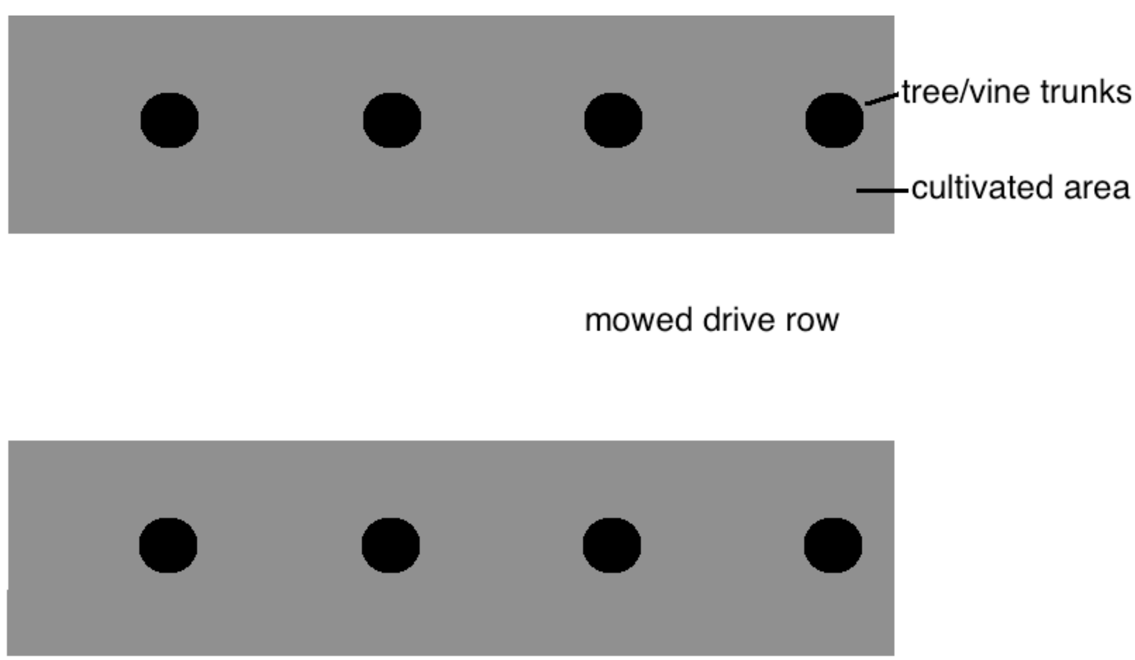


**Figure 2. Sketch of in-row strip tillage**. Overhead view, with black circles denoting tree or vine trunks, and grey area denoting cultivated area.

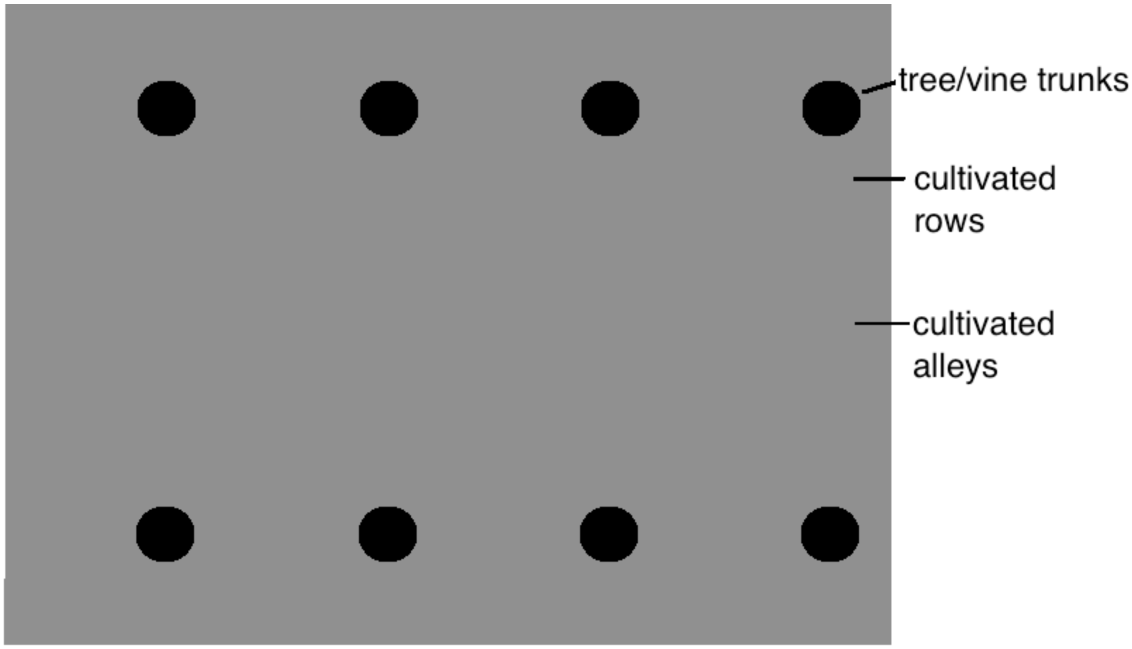


**Figure 3. Sketch of clean cultivation**. Overhead view, with black circles denoting tree or vine trunks, and grey area denoting cultivated area.

Figure 5. Clemens radius hoe.

Figure 4. Wonder-weeder in use.

Figure 6. Radius hoe in use.

Currently strip cultivation is most commonly done in organic systems, where it has been found to be an effective weed management strategy. A four-year vineyard study by Pool et al. (1990) showed that, between herbicide application and cultivation, there was no difference in yield, cane pruning weights, or soluble solids content (degrees Brix) in the crop. Work with young apple tree plantings has showed that cultivation is effective at removing weed competition, without the risk of toxicity to the trees that herbicide application brings (Hogue and Neilsen 1987). Cultivation can also be combined with other weed management tactics - e.g. properly timed tillage of re-seeding annual cover crop releases stored nutrients from the cover crop.

Previous research on strip cultivation has implicated it in nutrient leaching and loss of organic matter (Merwin et al. 1994, Merwin 2003, Hogue and Neilsen 1987). However, these studies have largely been done using Power-takeoff-driven cultivators, which cause a heavy disturbance of the soil (Merwin and Stiles, 1994). In a study by Stefanelli et al. (2009) in Michigan using a notch disk tiller, soil organic matter increased slightly over the course of four years. Many studies have also been done in low-rainfall environments such as Northern California and Eastern Washington, where weed recovery is relatively slow (Hogue and Neilsen 1987). However, weed recovery is faster in the Eastern United states, which has higher rainfall. Since in wet environments ground vegetation recovers more quickly, soil nutrients not used by the crop can be retained by weed growth (Haynes 1986). This is of particular interest with grapes, which have a low soil N use efficiency (Vos et al. 2004). As stated by Granatstein and Sanchez (2009), "no single practice or set of practices is likely to perform equally well across the wide range of climatic, soil, and orchard conditions..." Context determines results; this is particularly true in the case of ground management. For these reasons, our purpose was to investigate the system-wide impacts of strip cultivation applied to two perennial fruit systems in Michigan.

**Nitrogen Dynamics**

Nitrogen (N) is the most often limiting nutrient in plants, including both grape vines and apple trees (Keller 2010) and the movement and conversion of N to its several forms in the soil and in plants - ammonium ($NH_4^+$), nitrate ($NO_3^-$), gaseous dinitrogen ($N_2$), organic acids, amino acids, and proteins - is complex. The processes governing these changes are: N Fixation, nitrification, denitrification, mineralization, immobilization, fertilizer application, plant root uptake, plant enzymatic reactions, adsorption to soil particles, and rainfall. The latter influences both the amount of soil moisture present and the process of leaching. The first three processes are reduction / oxidation reactions and are beyond the scope of this study.

**Mineralization and Immobilization**

The processes of N mineralization and immobilization each occur after the incorporation of agricultural residues into soils (Stevenson and Cole 1999). Immobilization is the process that occurs after the addition of a high-carbon resource to the soil, where available N in the soil solution is taken up by bacteria and fungi to consume the resource (Stevenson and Cole 1999). Mineralization refers to the addition of a low-carbon resource to the soil, after which N is converted to a soluble form. Which of the two processes occurs depends on the carbon to nitrogen ration (C:N) of the organic material added. After plant residues are added to a normal high-oxygen soil, 2/3 of the C from a resource is released as fully oxidized $CO_2$, and 1/3 is utilized by microorganisms to build their own biomass (Haynes 1986). Because the mean C:N ratio of microbes is approximately 8:1, the critical C:N ratio of organic materials added to the soil is 24:1. Above this ratio, N immobilization occurs for some period before the N in the residue is released as inorganic N. Below this ratio, N mineralization occurs more immediately, in some cases without first being immobilized (Haynes 1986).

The discussion of N mineralization and immobilization is relevant in the case of strip cultivation because each cultivation event adds weed biomass to the soil. Weed species tend to have a very low C:N ratio. For example, common lambsquarters (*Chenopodium album* L.) ranges from 9.4 to 13.0, and *Ambrosia atemisiifolia* L. ranges from 8.0 to 14.2 (Lindsey et al. 2013). These low C:N ratios indicate that mineralization is likely to occur, rather than immobilization (Toselli et. al. 2011).

**Root Uptake**

Plants take up N by active transport, usually of $NO_3^-$, which allows them to have much higher concentration of inorganic N ions in both root hairs and xylem tissue than the surrounding soil solution (Keller 2010). Much of the N needs for the season are met through stored N from previous years' uptake: up to 40% in apples, and the majority of fruit N in grapes (Conradie 1981, Sanchez et al. 1995). However, N uptake by plant roots does vary over the course of the season, and is highest during the period of most rapid vegetative growth and fruit maturation. Making nutrients available to crops at the appropriate time improves both growth and fruiting. Merwin and Ray (1997) kept constant the length of herbicide-mediated weed-free time (several weeks) in the orchard, but varied the time of year at which the ground was kept clear. Their earliest weed-free period (May) resulted in the highest yield, and progressively later weed-free periods resulted in lower yield. As a result of this intra-seasonal uptake pattern, timing the recovery of ground vegetation for both applied N and stored soil N is necessary to ensure access to nutrients at the proper time.

An N-partitioning study by Ter Avest et al. (2010) showed the impact of ground management on N in apple trees. Trees under wood mulch had more woody growth than those under cultivation or legume cover crops, yet the trees responded to the different treatments by partitioning N differently in their tissues, resulting in *similar yields*. Also, they found that spring N uptake was used in fruits and shoots, whereas summer N uptake was used in growth of perennial tissues, indicating that spring and early-summer N availability determine crop weight more than mid- to late-summer N availability (Ter Avest et al. 2010).

For grapes, in regions with long enough growing seasons that leaves are present on the vines for up to several months after harvest, significant N uptake occurs between harvest and leaf fall (Conradie 1986, Hanson and Howell 1995). However, work in short-season grapes has shown that most N uptake occurs over the period from shortly before bloom until veraison (Hanson and Howell 1995, Bates et al. 2002, Pradubsuk and Davenport 2010). Therefore this is the period it is most important to remove competition for N from weeds. Further, dormant-season mineral N application is generally leached before it can be used, particularly if it is applied as a salt of Nitrate (Peacock et al. 1982, Hajrasuliha 1998).

**Fertilizer Application**

Since the discovery by Haber and Bosch of N fixation by electrolysis, anthropogenic inputs have entered the N cycle as an abundant source of available N, particularly in agroecosystems (Haynes 1986). Prior to this discovery, addition of available N to cropping systems was limited to addition of low C:N ratio organic residues such as manures, or incorporation of legumes (Fabaceae), e.g. beans, soybeans, peas, clover, or vetch (Haynes 1986). Fruit N lost from harvest must be replaced each year. In the case of vineyards and apple orchards, 1-2 kg N / ton of fruit is lost each grape harvest (Mullins et al. 1992), and about 40 kg N / ha of orchard is lost each apple harvest (Jackson et al. 2011). In order for a mineral fertilizer application to be made available to crop plants, the area to which it is applied must be clear of competitors for the resource - both apples and grapes are inefficient at N uptake, and weed species tend to be efficient (Mullins et al. 1992, Merwin 2003).

Organic fruit growers use little or no mineral N. Therefore conservation of soil N is more critical for organic fruit. Any applied N in the form of manures and other low C:N materials which is not immediately used by the crop must be retained in the soil in one form or another, and kept from being leached or denitrified. They are retained if used by weeds or a cover crop until they are tilled under to re-mineralize the N (Granatstein and Sanchez 2009).

**Leaching**

Frequently, fertilizers and organic residues added to the soil surface or incorporated contain soluble N in excess of a level usable by the crop. Grapes, for example, often display very low N use efficiency at typical fertilizer application levels (Vos et al. 2004). In this case, $NO_3^-$ will leach downwards in the soil profile (Baker et al. 1975). This occurs at a faster rate with increasing mean soil particle size, and with decreasing organic matter content, and is exacerbated in tile-drained soils (Dinnes et al. 2002). Though radio-labelling studies have revealed that most of the leaching $NO_3^-$ in an orchard system comes from soil organic N breakdown, rather than from fertilizer-applied N (Toselli et al. 2011).

**Soil particle adsorption**

$NH_4^+$ in the soil solution is available for adsorption to the Cation Exchange Capacity (CEC) of soil particles. This is of interest in soils with high clay content or organic matter content, which also have a high CEC (Bohn 2001). Indeed in many soils, most of the $NH_4^+$ present is adsorbed to the CEC and unavailable for use by plants and microbes (Bohn 2001). In contrast $NO_3^-$ cannot adsorb to soil particles because it is anionic, and is either used or lost very quickly to leaching. Adsorbed NH4+ is in constant equilibrium with solution NH4+, which is in turn in equilibrium with solution with NO3-; therefore even adsorbed N will be slowly lost from the system when there are no plant roots taking it up (Stevenson and Cole 1999).

**Soil moisture**

Water relations are an important determinant of nutrient uptake in perennial fruit. Soil moisture also contributes to plants' ability to access nutrients (Walsh et al. 1996). Uptake of nutrients by roots is an aqueous process - without a soil water solution from which to absorb ions, none can be absorbed. So availability of water determines availability of even abundant soil nutrients to plants (Keller 2010). Thus, water stress on a tree or vine typically results in nutrient stress. Ironically, plants that have historically not been irrigated are more successful in water-stressed environments. This is because vines and trees being irrigated tend to concentrate their root growth in the top few cm of the irrigated zone (Layne et. al 1986, Mullins 1992), whereas trees and vines that have not been irrigated are more likely to develop sinker roots, and to develop more feeder roots at deeper strata, which brings up water to shallow soil layers (Layne et al. 1986, Keller 2010).

Rooting in apples also depends on characteristics of selected rootstocks: more vigorous rootstocks tend to form deeper and sturdier root structures than dwarfing rootstocks used in modern high-density plantings, such as MM.9 and MM.26 (Webster 1993, Fernandez et al. 1995). In grapes, seedling rootstocks of both *V. vinifera* and *V. labruscana* tend to form sinker roots with lateral branches, whereas less-vigorous hybrid rootstocks concentrate their growth in the top layer (Keller 2010). Deeper rooting systems can draw water not only into the plant itself, but also into shallower soil strata, creating a soil solution to make nutrients there available (Fernandez et. al. 1997, Keller 2010).

**Water and Nitrogen in Wine Grapes**

This research was concerned with apples and wine grapes. Both apples and juice grapes have similar demands in fruit quality and yield: growers are generally attempting to maximize yield while remaining above a minimum threshold of fruit quality. Wine grapes, on the other hand, (*V. vinifera* and hybrids) are grown in a rather different economic context - wine grapes have a more narrow and difficult to achieve quality expectations, rather different than those for juice grapes. High cropping levels can depress quality parameters needed for high-quality fruit (Mullins et al. 1992). Higher cropping levels also cause slower fruit maturation, which is critical to wine quality in colder-weather grape growing regions (Jackson and Lombard 1993). Therefore higher quality grapes for wine often come from soils with lower N content or water content (Jackson and Lombard 1993). Thus, there is more interest in cover cropping in wine grapes because more competition for water and nitrogen can yield improved fruit (Wheeler et al. 2005).

## Soil Organic Matter

Soil organic matter (SOM) consists of the accumulation of organic residues in soil that have not been completely broken down to mineral forms by micro-organisms (Stevenson and Cole 1999). Sufficient SOM is habitat and food for microorganisms, an adsorption surface for N and other nutrients. Structurally, it prevents compaction after tilling, creates pore space, and improves water-holding capacity. Further, the complex organic structure of SOM provides a buffer to prevent rapid changes in pH (Bohn 2001).

Ground management has an impact on soil organic matter. As stated above, cultivation can either increase or decrease soil organic matter content, depending on the implement, timing, soil, and rainfall. Organic matter content in the row increases under cover crops (Smith et al. 2001, Sanchez et al. 2003). Plant residue or compost mulches can also be used to increase soil organic matter (Sanchez et al. 2003, Peck et al. 2011). Decreases in organic matter have been recorded from herbicide strip areas over the long term (Hogue and

Nielsen 1987, Hipps and Samuelson 1991). In a study conducted by Zoppolo et. al. (2011), SOM increased under the Swiss sandwich system, without external inputs. The explanation for this is that residues from weed cover repeatedly incorporated into the soil provided a net increase in SOM.

## Influence of Strip Cultivation on Insect Pest Management

Choice of ground floor management tactics may have a direct influence on insect pest management: cultivation over insect pests while they are in the soil or on the soil surface may either reduce their survival, increase their survival, or have no effect. If it reduces their survival, possible sources of mortality include direct mechanical damage, physical inability to remove themselves from a buried state, exposure to soil microorganisms, or exposure to predators. Ground floor management may also influence pest populations by altering habitat for both parasitoids and predators. Two economically important pests of apple are the plum curculio, *Conotrachelus nenuphar* Herbst (Coleoptera: Curculionidae) and the codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae). Their life cycles are discussed below, with attention given to the circumstances under which they are targetable on the orchard floor.

### Life Cycle of Plum Curculio

*Conotrachelus nenuphar* is a pest of a number of fruit crops in the Rosaceae — notably cherries, peaches, plums, apples, and pears. It is univoltine in Michigan. Its life cycle is as follows: adults break diapause during or shortly after fruit set and migrate into orchards to feed on developing apples and mate, after which females lay eggs in the young fruit (Smith and Flessel 1968).

Oviposition usually occurs within 2 weeks of entering the orchard (Lan et al. 2004). Larvae feed and develop internally for four instars. The tree excises most infested apples during June drop (Paradis 1957). Larvae infesting apples that remain on the tree are often killed by the increased turgor pressure of the fruit as it develops, but those that survive eventually exit the fruit and drop to the orchard floor (Paradis 1957). The most reliable phenological model is by Lan et al. (2004), which was developed for the Southern strain. The threshold temperature for larval development is 11.1 °C; they pupate at 215 degree days above this threshold, at which point they exit the fruit, burrow underground, and pupate (Lan et al. 2004). The pupal development threshold is 8.7 °C, and they emerge as adults 442 degree days above this threshold. Adults emerge in late summer, feed on mature fruit, and seek a refuge in which to diapause for the fall and winter (Racette et al. 1992).

Cultivation may be able to target the plum curculio at two times: when the larvae are still in the dropped apples on the ground, and when the adults enter diapause for the winter. However, adult *C. nenuphar* are reported to leave the orchard environment to overwinter in adjacent habitats, making it impractical to target them at that time of the year (Lafleur et al. 1987, Racette et al. 1992). Therefore, if it is possible to kill or inhibit plum curculio with a cultivator, then the period of larval development in dropped apples and pupation in the soil is when they will be vulnerable to cultivation-mediated mortality. Buehrer (unpublished) has shown that domestic hogs ranged in the orchard at this time significantly reduced the recruitment into the adult stage in both cherries and apples.

**Life Cycle of Codling Moth**

*Cydia pomonella* have a different life cycle than plum curculio, requiring different cultivation timings to target vulnerable stages. In Michigan, there are two generations of *C. pomonella*. The developmental threshold for this pest is 10°C (Howell and Neven 2000). The codling moth life cycle begins with late-instars from the previous year's second generation breaking diapause and pupating in the spring, subsequently emerging as adults. Navigating by pheromones produced by the female, flying males find and mate with females (Geier 1963). Females lay eggs on the surface of leaves or developing apples; peak egg laying occurs at 306 degree days (DD) above the develomental threshold. After hatching, which begins at 695 DD, larvae enter the apple to feed. Larvae exit the developing apples and find a dry, sheltered place to pupate. The next generation emerges as adults at 890 DD and repeats the cycle, egg-laying occurring around 945 DD. The second generation of 5$^{th}$ instars diapause as cocooned larvae for the winter.

Two factors are likely to affect the ability of cultivation to interrupt codling moth populations: 1) the location of their pupation and/or diapause sites and 2) phenology. *C. pomonella* pupate in splits, injuries, and pruning wounds, and in rough-barked apple trees they also pupate on crevices on tree bark (Geier 1963, Blomefield and Giliomee 2012). In an orchard with smoother-barked trees, larvae are believed to pupate in the leaf litter and on prunings or other debris on the ground (Slingerland 1898, Crosby and Leonard 1914). If so, cultivation is likely to intercept more codling moth in orchards with smooth-barked trees, where larvae would be forced to pupate on the soil surface.

The timing and phenology of the two codling moth generations is also likely to affect the utility of cultivation as a management tool. The first generation of codling moth pupates over several summer months with individuals emerging throughout this period. In contrast, the second generation ceases development as they enter diapause. Thus, if cultivation can reduce codling moth populations, treatments targeting codling moth on the orchard floor are likely to be more effective when focusing on the second generation with passes made in the late fall or early spring.

**Natural Enemy Habitat**

The choice of floor management tactics, and the amount of weeds left on the surface, may improve or reduce natural enemy habitat and in turn affect pest populations. Greater surface weed cover has been shown to facilitate greater populations of ground predators, including spiders in table grape vineyards (Costello and Daane 1998), carabids in cabbage fields (Armstrong and McKinlay 1997), enemies of the red citrus mite in citrus orchards (Liang and Huang 1994), predatory beetles in winter wheat (Powell et al. 1985), and spiders in olive orchards (Paredes et al. 2013). The difference has been attributed variously to the presence of plant food resources, other arthropod food resources, and shelter from intraguild predation (Barbosa 1998, Altieri and Whitcomb 1979). In a few cases, there is direct evidence of negative impact on pest insect populations or proportion of crop damaged, due a difference in predator populations from increased weed cover. This has been shown for fall armyworm and aphids in field corn (Penagos et al. 2003), and for management of the red citrus mite (Liang and Huang 1994).

Conversely, Aguyoh et al. (2004) showed an increase in bean leaf beetle and crop damage from increased weed cover in snap bean plots. These and other examples compel us to consider each case individually: whether an increase in weed cover will hinder or help pest insects depends on the natural enemy complex present, and the pest itself. One interesting question in this vein is: if there *is* a difference in ground predator presence resulting from a change in ground cover amount, is it due to increased survival and reproduction of predators already present, or due to immigration via environmental cues in the understory? Bergelson and Karelva (1987) addressed this in the context of flea beetles in collard green plantings; they found that differences in flea beetle populations were greater where there were no barriers to movement between ground cover treatments, indicating that "patch choice" plays a major role. In some cases, however, we can assume that the effect of both emigration and birth/death rate will accumulate to some degree over time: one or two years may not be sufficient to fully assess the difference between habitats for natural enemy populations. All this must be considered when comparing insect population estimates from different environments such as those created by two different ground management strategies.

Experiments measuring natural enemy population differences between plots where different ground management strategies have been employed have had mixed results. Miñarro and Dapena (2003) found that ground beetle populations in apple orchards were higher in tilled plots than in either mulch or herbicide treatments. Their species composition also varies by cropping system, and management system within a given crop (Clark et al. 1997).

Other researchers have observed differences in natural enemy populations between conventionally-managed and organically-managed plantings (Knight 1994). Much of this difference is attributable to differences in insecticide use - for example, Epstein et al. (2001) found that populations of *Pterostichus adstrictus* and *P. melanarius* (Coleoptera: Carabidae) were significantly reduced by pest management tactics using neurotoxic insecticides in comparison with pest management with more selective controls such as pheromone mating disruption. Similar comparisons have been made by many researchers, often with similar results: insecticides intended to target pest insects can also have a negative impact on natural enemy populations, and they therefore are less abundant in insecticide-treated orchards and vineyards (Mates et al. 2012).

**Natural Enemies of the Plum Curculio**

Plum curculio are most vulnerable to predation and parasitism when they are mature larvae leaving the excised fruit to enter the soil for pupation. At this stage they are exposed and unsclerotized (Racette et al. 1992). The ants *Solenopsis invicta* and *Dorymyrmex bureni* have both been shown to feed on mature plum curculio larvae in the field, causing up to 60% mortality in the test orchards used by Jenkins et al. (2006) in Georgia and Florida. They also recorded the parasitoids *Nealiolus curculionis* Fitch (Hymenoptera: Braconidae) and *Cholomyia inaequipes* Bigot (Diptera: Tachinidae) in larvae in the field. Quaintance and Jenne (1912) described a number of parasitoid insects successfully reared from field-caught *C. nenuphar*: *Anaphoidea conotracheli* Girault (Mymaridae), *Triaspis curculionis* Fitch (Braconidae), *Thersilochus conotracheli* Riley (Ichneumonidae), *Microbracon mellitor* Say (Braconidae), *Myiophasia aenea* Wiedemann (Tabanidae), *Cholomyia inaequipes* Bigot (Tabanidae) but these parasitoids are not necessarily economically effective biological control agents. Other predators described by Quaintance and Jenne in an anecdotal fashion included: *Chrysopa* larvae (Neuroptera: Chrysopidae) and adults of the species *Harpalus pensylvanicus* Degeer*, H. faunus* Say*, Evarthrus orbatus* Newman*, and E. obsoletus* Le Conte (all Coleoptera: Carabidae). Carabid beetles and ants were confirmed as predators of plum curculio by several early authors (Howard 1906, Snapp 1930). Predation of the egg and earlier larval stages is not known to occur because eggs and larvae are found only on the inside of fruit.

**Natural Enemies of the Codling Moth**

*Trichogramma minutum* (Trichogrammatidae) and *Ascogaster quadridentata* (Braconidae) are both confirmed and abundant egg parasitoids of codling moth in orchards (Walton 2013). Other egg predators confirmed to make an impact on *C. pomonella* populations in orchards include *Chrysopa* spp. (Neuroptera: Chrysopidae), the green lacewing larva; thrips species *Haplothris faurei* Hood and *Leptothrips mali* Fitch (Thysanoptera: Phlaeothripidae), and a number of Coccinellid beetle adults, namely *Anatis quindecimpunctata* DeGeer, *Hippodamia convergens* Guerin, and *Coccinella nevomnotata* Herbst. The common earwing, *Forficula auricularia* L. (Dermaptera: Forficulidae) is an abundant, widespread, and voracious predator of codling moth eggs. Several members of the Hemipteran families Miridae and Anthocoridae have been noted to consume them as well (Jaynes and Marucci 1947, Ferro et al. 1975, Walton 2013).

Fifth instars that have exited the apple and are seeking a cocooning site, cocooned fifth-instars, and pupae, have a set of predators and parasitoids that is different than the predator complex of the eggs and neonates (Walton 2013). Songbirds often provide the greatest depredation in these stages, particularly woodpeckers (Piciformes: Picidae) (MacLellan 1958, 1962). Arthropod predators include the ants *Solenopsis molesta* Say, *Formica fusca* Say and *Monomorium* spp. (Hymenoptera: Formicidae), *Tenebroides corticalis* Melsh (Coleoptera: Trogrossitidae), larvae of *Chauliognathus spp.* (Coleoptera: Cantharidae), *Conderus lividus* De Geer (Coleoptera: Elateridae), as well as a variety of spiders (Aranae) and larvae and adults of ground beetles (Coleoptera: Carabidae) (Jaynes and Marucci 1947, Walton 2013). Of the Carabids, *Pterostichus melinarius* Bonelli has been observed consuming pupae and fifth-instars in the laboratory (Epstein et al. 2001), and has been repeatedly implicated as the most effective predator of late-stage *C. pomonella* larvae (Hagley et al. 1982, Hagley and Allen 1988, Riddick and Mills 1994). The primary parasitoids targeting these later life stages are *Ascogaster quadridentata* Brunner (Hymenoptera:

Braconidae) which also targets eggs and neonates (Jaynes and Marucci 1947), *Mastrus ridibundis*, and *Liotryphon punctulatus* (both Ichneumonidae) (Mills 2005).

Little information is available on which species of insects, if any, feed on adult codling moth. This is due to the many obstacles to studying predation of flighted organisms. No predation during the internal fruit-feeding stage is known, except by cannibalism (Walton 2013).

The arthropods that spend the most time foraging in the understory are the most likely to be affected by a change in ground management; an increase in ground vegetation may decrease their foraging efficiency (Mathews et al. 2004). Whereas, an increase in habitat complexity can also increase their population either due to more abundant alternative resources, or by providing refuge from intraguild predation (Langellotto and Denno 2004). Those listed above which also forage in the understory are: the Formicidae, Carabidae, Aranae, Forficulidae, and larvae of the Chrysopidae.

**Direct Pest Disruption Using Cultivation**

The majority of insects spend some part of their life cycle in the soil, lending possibility to destruction by soil disturbance (Pedigo 1989). In some situations this allows for effective management of the pest using tillage, particularly in concert with other cultural techniques. However, cultural management techniques often do not have the efficacy to sufficiently manage pests during a serious infestation, and must be used in concert with other methods (Dent 2000).

Cultivation is used for insect pest management strategy in annual crops, where the presence of bare soil at least once a year affords an opportunity to affect pest populations with soil disturbance. This is most commonly done in cotton and maize (Stinner and House 1990). In cotton, destruction of plant residues by flailing, mowing, or tilling kills bollworm, *Pectinophora gossypiella* Saunders (Lepidoptera: Gelichiidae) larvae (Adkisson et al. 1960). For example, a cultural management plan including a Nov. 1 plowdown, early planting, and a defoliant spray before harvest reduced bollworm damage the next year by 90% (Chu et al. 1996). Tillage is also used as a management strategy for white grubs, termites, mealybugs, and scale insects in cotton (Russell 2004).

In maize, plowing under residues has been shown to make them unavailable as an overwintering site for black cutworm *Agrotis ipsilon* Hufnagel (Lepidoptera: Noctuidea) (Johnson et al. 1984). Loss of this advantage has been problematic for growers adapting a no-till program (Stinner and House 1990). In Ohio, it has been shown that as tillage frequency is reduced, black cutworm, stalk borer, armyworms, and slug populations increase (Willson and Eisley 1992). Conversely, in a trial by Brust et al. (1985), predator populations were lower and black cutworm populations higher in the tillage treatment compared to the no-till.

There are further examples from other crops where partial management of insect pests is possible using soil disturbance and destruction of plant residues. Similar to studies in corn, in canola more damage is observed from the flea beetles *Phyllotreta cruciferae* Goeze and *P. striolata* Fabricius (Coleoptera, Chrysomelidae) in no-till plots compared to conventional-tillage plots (Milbrath et al. 1995, Dosdall et al. 1999). The same difference has been observed with the green cloverworm, *Plathypena scabra* Fabricius (Lepidoptera: Erebidae) in soybean fields. In trials in both peanuts and sweet potatoes, tillage was shown to reduce wireworm (Coleoptera: Elateridae) damage (Scarpellini et al. 2004, Seal et al. 1992). In peppermint, tillage reduced the emergence of mint root borer, *Fumibotys fumalis* Guenée (Lepidoptera: Crambidae) by 80% (Pike and Glazer 1982). Unfortunately, research on cultural control tactics such as cultivation lacks the economic incentive offered by research centered on product development, so less research is done to address these questions (Dent 2000).

There are also examples of recommendations in perennial fruit for insect pest control via soil disturbance. For example, throwing up a furrow onto the vinerows was at one time recommended as a means of Grape Berry Moth (Tortricidae: *Paralobesia viteana* Clemens) control, and some rudimentary trials have indicated that emerging adults are unable to dig upwards through an inch or two of soil (Isely 1917). Conversely, work with codling moth has indicated that they may be capable of digging out of six inches of soil (Steiner 1929). Gut et al. (2005) showed that soil mounding over the graft union in new apple plantings can greatly reduce infestation by the dogwood borer *Synanthedon scitula* Harris (Lepidoptera: Sesiidae). Beyond the studies described above, the question of cultivation effects on pest survival has not been addressed in perennial fruit.

## Objectives of the Present Work

The goals of this research were to: 1) Compare Swiss sandwich system and in-row strip tillage to herbicide application in apple and grape systems, addressing soil mineral N and organic matter 2) Assess the impact of strip cultivation compared to herbicide application on arthropod natural enemies; and 3) Assess the potential impact of strip cultivation on codling moth and plum curculio populations in orchards.

## CHAPTER TWO: GROUND COVER, SOIL NITROGEN, AND PREDATOR COMMUNITY RESPONSE TO STRIP CULTIVATION IN APPLE AND GRAPE

### Introduction

Ground floor management in perennial fruit affects many aspects of the crop environment. Competition of ground vegetation for water and nutrients determines vegetative growth, tree or vine development, fruit weight, and fruit quality parameters (Hogue and Neilsen 1987, Guerra and Steenworth 2012, Mullins et al. 1992, Neilsen and Neilsen 2003). Floor management also affects soil organic matter formation and breakdown, which determines soil water and nutrient-holding capacity (Zoppolo et al. 2011, Oliviera and Merwin 2001). Ground vegetation type, density, and maturity also determines food resources, attractiveness, and navigability of orchard and vineyard environments for natural enemies (Pedigo 1989).

Available soil management strategies include herbicide strip, flame weeding, cover cropping, mulching, and strip cultivation (Hogue and Neilsen 1987). The term strip cultivation describes a floor management treatment wherein native vegetation is maintained in the drive rows with mowing, and the area in the tree rows is cultivated several times a year (Weibel 2002). Two versions of this technique are as follows: 1. In the Swiss Sandwich System (Figure 1, pg. 9), a narrow strip in the tree- or vine-rows is left untilled and native vegetation is allowed to grow freely (Weibel 2002). e.g. with a notch disc tiller, tooth arrow tiller, or spider tines implement (Figure 4, pg. 11) 2. In-Row Strip Tillage (Figure 2, pg. 9) refers to a system wherein the whole in-row area is cultivated. In-Row Strip Tillage necessitates an implement capable of lateral movement with respect to the tractor, such as a radial hoe (Figures 5 and 6, pg. 11).

Nitrogen (N) is the most often limiting nutrient in plants, including both grape vines and apple trees (Jackson et al. 2011). Management of ground vegetation can alter available water and N to the crop in several ways. Understory vegetation will take up inorganic fertilizer applications, which can reduce available N to the crop at critical uptake times (Bedford and Pickering 1914). However, a fruit grower can use this uptake event to allow ground vegetation to store excess N from fertilizer applications, as well as native soil N to prevent leaching; this N can be released by incorporating the weeds with a later cultivation event. In order to do so, it must be known when peak demand for fruit N occurs, and how long mineralization will take to occur after weed incorporation. Further, weed cover can be used to reduce available water and nutrients to reduce undesirable vegetative growth, and increase fruit quality parameters (Jackson and Lombard 1993).

Several studies have shown a reduction in soil organic matter content from cultivation in perennial fruit environments (Merwin et al. 1994, Merwin and Stiles 1994, Hogue and Neilsen 1987). These studies were done either in low-rainfall environments such as the Western U.S., or with high-impact PTO-driven cultivating implements such as a rototiller or weed badger. Studies in higher-rainfall environments using lower-impact, ground-driven cultivating implements such as a notch disc tiller or spider implement show either no impact on, or an increase in, soil organic matter content, presumably due to a continually-rebounding weed cover (Zopollo et al. 2011).

Strip cultivation may also create a different environment than herbicide application for orchard and vineyard natural enemies, particularly ground predators. Different weed species may prevail under the different ground management regime, offering increased or decreased alternative food resources. In situations where there is greater ground cover under strip cultivation than under herbicide, greater shelter may arrest or attract predator species in the orchard floor environment, which could increase biological control services. Surface weed cover has been shown to facilitate higher populations of ground predators, including spiders in table grape vineyards (Costello and Daane 1998), carabids in cabbage fields (Armstrong and McKinlay 1997), enemies of the red citrus mite in citrus orchards (Liang and Huang 1994), predatory beetles in winter wheat (Powell et al. 1985), and spiders in olive orchards (Paredes et al. 2013). Alternatively, increased ground cover could provide higher habitat complexity, reducing predator ability to locate prey items, thereby reducing biological control services. In any case, the effect of ground management technique on natural enemy activity-density is more pronounced in organic systems, where a lack of broad-spectrum insecticides allows much greater build-up of natural enemy populations (Epstein 2011).

## Objectives

The objective of the work described here was to compare strip cultivation to herbicide application in two perennial fruit systems. The following specific questions were addressed quantitatively:

a. Is there an observable difference in the quantity of inorganic N in the soil following a cultivation event, both with and without an input of organic N sources, and if so, how long does the change take to occur?

b. Is there a difference in tree or vine nutrition reflected in leaf N content between the herbicide and cultivation treatments?

c. Is there a difference in either the abundance or activity of natural enemies on the orchard and vineyard floor between cultivation and herbicide treatments?

d. Is there a reduction of organic matter content in the soil over several years in either or both treatments?

## Materials and Methods

One commercial apple orchard and one commercial wine grape vineyard were used as sites for this project. The vineyard site was Chateau Chantal, Traverse City, Michigan (N44.8262 W85.5610). The apple orchard was the Country Mill, Charlotte, Michigan (N42.6332 W84.7977). All data were collected in 2012 and 2013. Comparisons were made between strip cultivation treatments and herbicide treatment at both sites.

## Description of Field Sites and Floor Management Treatments

At the vineyard site in early 2012, six plots were assigned, with three replicates for each of two ground cover treatments: in-row strip tillage, and herbicide application. Vines are 198 Riesling on 5BB rootstock, planted on 3m x 1.5m spacing in 1996, were irrigated 1996-2000, and trellised in vertical shoot position. The treatments were maintained in 2012 and 2013, and data were taken in both years. Ground cover at this site was primarily grasses, clover, vetch, spotted knapweed, alyssum, plantain, and ragweed. Soils are Emmet sandy loam. Prior to the study, weed management was with glyphosate using similar formulations to those used during the experiment (see below). Diseases and insect pests at this vineyard are actively managed with a diverse array of pesticides varying year to year.

The orchard area was divided into six plots ranging from 1.4-4.3 acres, for three replicates of each of the two ground cover treatments, Swiss sandwich system or herbicide application, from 2010 to 2013. The trees in the experimental plots were planted in 1977 and 1985 on M.111, alternating scion varieties every one to four rows. The varieties were Ida Red, Golden Delicious, McIntosh, Paula Red, Honeycrisp, Jonagold, Red Delicious, Gala, Summer Treat, Mollie's Delicious, Empire, Spygold, and Fuji. Data was taken during 2012 and 2013. Ground cover at this site is primarily grasses, plantain, poison ivy, clingers, dandelion and clover, and soils are a mixture of Marlette and Capac loam. Before 2010, weed management was maintenance of an herbicide strip in all rows using primarily simazine (6-Chloro-*N*,*N′*-diethyl-1,3,5-triazine-2,4-

diamine) and glyphosate (N-phosphonomethylglycine). No nitrogen or phosphorus fertilizer applications were made in 2010 - 2013. Due to early warm weather in spring, and several late frosts, there was no apple fruit set in 2012.

At the vineyard site, the in-row strip tillage treatment consisted of a single pass with a Clemens Radius Hoe ® (Clemens Vineyard Equipment, Wittlich, Germany) on each side of the vine rows on April 20, May 21, and June 28, 2012, and April 6, May 7, June 24, and July 21, 2013. The herbicide treatment consisted of application of glyphosate at 0.3 l/acre on May 1 and June 21, 2012, 2 liter/acre May 27, 2013, and carfentrazone (2-chloro-3-(2-chloro-5-[4-(difluoromethyl)-4,5-dihydro-3-methyl-5-oxo-1*H*-1,2,4-triazol-1-yl]-4-fluorophenyl)propionic acid) at 60 g/acre on July 23, 2013. Both treatments received an application of finished poultry manure compost on the first week of May, 2012.

At the orchard site, the Swiss sandwich system treatment consisted of a single pass with a Wonder Weeder ® (Harris Manufacturing, Burbank, WA), a Lilliston-style cultivator, on each of the following dates: March 18, June 2, and July 23, 2012, and April 23, May 31, and July 10, 2013. The Wonder Weeder was run 3 to 6 inches below the surface. The herbicide treatment consisted of application on April 23, 2012 of glyphosate at 1.4 liters/acre and simazine at 3.8 liters/acre, and on May 2, 2013 of glyphosate at 1.9 liters/acre, terbacil (3-tert-butyl-5-chloro-6-methyluracil) at 1.1 kg/acre simazine at 3.8 liters/acre.

## Data Collection

To quantify ground cover, 30 m transects per plot were established directly in the strip of ground where the treatment was applied, on the East side of the tree- or vine-rows. A random numbers generator was used to determine the row in which these transects were located, and their location in the row. A 20 x 50 cm PVC Daubenmire frame was set down along every m of the transects, and visual estimates of the percent cover to the nearest 5% within the frame recorded (Daubenmire 1959). This ground cover sampling method was done approximately once per month at each field site in 2012, and once every 14-16 days at each field site in 2013. Categories were as follows: bare ground, grass, forbs, moss, and apple/grape saplings. The grass and forbs percentages were totaled to a percent weed cover value, which was used for data analysis.

Ten soil cores per plot were collected from the cultivated area and from the herbicide strip. Cores were taken in a stratified random pattern evenly distributed throughout the plot. Cores were 18 cm deep, with a 10.5 cm diameter. These ten cores were pooled in a 5-gallon pail, mixed thoroughly in the field with a trowel and with shaking, and a composite sample of around 300 ml was taken from the bucket with a trowel. Samples were immediately placed in a cooler, and kept in a freezer for 1-4 days upon return to the lab, or submitted for analysis immediately. This process was repeated approximately once per month in 2012 and once every 14-16 days in 2013 from late spring until early fall. Soil organic matter was quantified using the Walkley-Black method (Brown 1998) in all 2012 samples and the first 2013 sample; total N was quantified using the Kjeldahl method in all 2013 samples (Bradstreet 1965); nitrate-N levels were quantified by cadmium reduction for all samples (Huffman and Barbarick 1981); ammonium-N levels were quantified using the salicylate method for all samples (Nelson 1983). All soil analyses were done by the Michigan State University Soil Plant and Nutrient Laboratory (1066 Bogue Street, Room A81; East Lansing, Michigan 48824).

For leaf and petiole nutrients, on July 10, 2013, 100 stratified-random leaf samples were collected from each of four rows (one each of Golden Delicious, MacIntosh, Ida Red, and Red Delicious) in each treatment, from the center of the current years' growth. On July 16, 2013, which was shortly after cap fall, 100 leaf petioles were picked from each of the six experimental plots (n=3 per treatment) Nitrogen content analysis for both was performed by the Michigan State University Soil and Plant Nutrient Laboratory (address in previous paragraph).

On September 27 and 28, 2013, 30 evenly-spaced trees were selected from each of one Red Delicious row in each of the two treatments. On each of these, we counted number of fruit per tree, picked 50 random fruit, weighed them, and used these data to estimate total fruit weight per tree.

Pitfall trap catches were used to estimate activity-density of several predator groups (Thiele 1977). 240 ml plastic cups were buried with the lip level even with the soil, with plywood rain covers 2 cm above soil level. In 2012, these contained commercial antifreeze; and in 2013 water and unscented dish soap. Six traps per plot in 2012 and five in 2013 were evenly spaced down the center tree or vine row. They were collected two weeks later, filtered and rinsed through a 1.3 mm mesh, and stored in 80% ethanol in vials at room temperature until counted under a dissecting microscope. Both immature and adult insect natural enemies were identified to suborder or family using keys by Stehr (1987) and Marshall (2006). Specimens of all insect taxa referred to in this thesis are deposited at the A.J. Cook Arthropod Collection at Michigan State University, according to the requirements of the Michigan State University Department of Entomology. Pitfall traps were collected at the vineyard on Jun 26, Jul 25, Aug 8, Aug 21, 2012, and Jun 20, Jul 30, and Aug 15, 2013, and at the orchard on Jun 21, Jul 6, Jul 19, Aug 18, 2012, and Jun 26, Jul 24, and Aug 6, 2013.

The prey removal set-up consisted of an index card with a small (1cm x 1cm) piece of paper towel on which eggs of the tobacco budworm, *Heliothis virescens* Fabricius (Lepidoptera: Noctuidae) had been laid in colony (French Agricultural Research in Lamberton, Minnesota). The starting number of eggs, recorded for each card, ranged from 10-20 on each unit. Four of these units were set up on a square of plywood with a rain cover in the center of the middle row of each plot at the orchard site on July 11, 16, and 23, and August 20, 2013. The number of eggs remaining was counted once per day, and the units were removed from the field after three days.

We also quantified insect damage. On June 17, 2013, 500 fruit, one from each of 500 trees evenly-spaced within the plot, at between 1-2 m height, on alternating corners of the tree canopy were selected (but not picked), in each of the six experimental plots at the orchard site. Fruit were inspected for codling moth stings, codling moth entry wounds, Oriental fruit moth *Grapholita molesta*

Busck (Lepidoptera, Tortricidae) stings, Oriental fruit moth entry wounds, and plum curculio stings.

**Statistical Analyses.**

Three separate analyses were performed on the ground cover data: Four ANOVA models of ground cover data - one per field site per year – were run using an arcsine transformation of the change in % weed cover (%weeds = %grass + %forbs) between adjacent sampling dates as the response variable, treatment (cultivation treated, herbicide treated, cultivation untreated, vs. herbicide untreated) as the fixed factor, and plot and transect as nested random factors. Secondly, to assess the difference in spatial variability between treatments, the variance/mean ratios of the % ground cover within each plot were calculated as an index of dispersion to determine which data set was more clumped, and analyzed with ANOVA models (Krebs 1999). Thirdly, to assess temporal variability between treatments, *t*-tests were performed on the absolute values of the percent change in ground cover between plots. For 2013 soil mineral N, mean and standard error of the change in mineral N content between several days following each cultivation event and two weeks thereafter were calculated. For each of grape petiole N, apple leaf N, and apple yield, *t*-tests were performed comparing the samples taken from the cultivation treatment to those taken from the herbicide treatment. A two-sample *t*-test was performed on soil organic matter data for each field site.

MANOVA models of pitfall trap data were constructed for each field site / year combination using trap catch as the response variable, treatment as the fixed factor, and date and plot as random variables. Of those returning significant values for treatment, individual ANOVA models were analyzed. A critical value of $\alpha = 0.10$ was used to determine significance. Mixed-model regressions of natural enemy catch against percent weed cover, using plot as a random factor run, for each taxonomic group / field site / year combination. Models returning a *p*-value below $\alpha = 0.10$ for any factor are reported.

For the prey removal experiment, I performed two Chi-squared analyses. The first compared the frequency distribution of four values - eggs removed on day one, on day two, on day three, and eggs left behind - between the two treatments. The second comparing the eggs left behind to those taken over all three days total. Orchard insect damage data from 2013 were not analyzed due to extremely low damage frequencies.

Costs per acre per year were calculated for each of the following ground management strategies: Swiss sandwich system with the Wonder Weeder ®**,** in-row strip tillage with the Clemens Radius Hoe ®, post-emergent herbicides, and pre-emergent herbicides. Calculations were made using the following assumptions: 5-year-old cultivating implement or sprayer, 100 acre orchard, 4 mph speed for the Lilliston cultivator, 1.5 mph speed for the radius hoe, and a 50 horsepower tractor. Tractor and implement depreciation costs came from an Iowa State University Machinery Cost Calculator formulated by William Edwards (https://www.extension.iastate.edu/agdm/crops/html/a3-29.html).

## Results

### Ground Cover

Percent weed cover decreased after each period in which a cultivation event occurred, and increased over untreated periods (Table 1 "Treated" and "Untreated", and Figures 7 and 8). A delayed response occurred in reduction in weed cover following an herbicide application. Differences between cultivation treated, herbicide treated, untreated cultivation plots, and untreated herbicide plots were found to be significant in all four experiments ($F = 131.7$, *d.f.* = 3, 2139, $p < 0.01$ for vineyard 2012; $F = 170.0$, *d.f.* = 3, 3759, $p < 0.01$ for vineyard 2013; $F = 695.5$, *d.f.* = 3, 3219, $p < 0.01$ for orchard 2012; $F = 317.3$, *d.f.* = 3, 4299, $p < 0.01$ for orchard 2013). Variance/mean ratios were greater in the herbicide treatment than in the cultivation treatments; i.e. more spatially variable, for the vineyard 2012 ($F = 10.3$, *d.f.* = 1,24, $p < 0.01$), orchard 2012 ($F = 5.7$, *d.f.* = 1,34, $p = 0.02$), and orchard 2013 ($F = 14.7$, *d.f.* = 1, 44, $p < 0.01$), but not for the vineyard 2013 ($F = 1.9$, *d.f.* = 2,38, $p = 0.16$). For the absolute value of the mean percent weed cover change, only at the orchard 2012 were these significantly different ($t = 4.1$, *d.f.* = 101.5, $p < 0.01$), where the Swiss sandwich treatment was found to be more dynamic than the herbicide treatment (Table 1, "All periods").

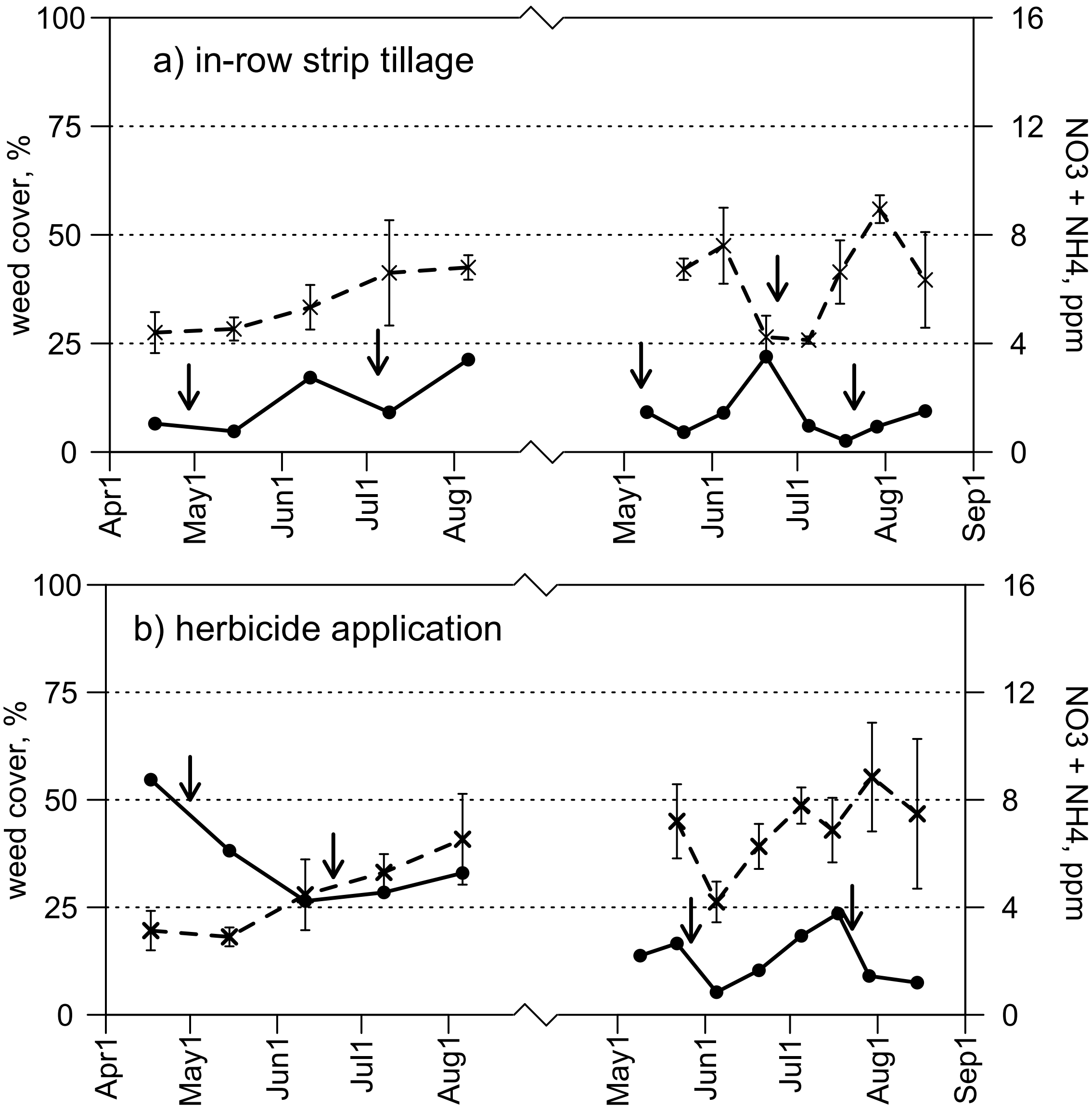


**Figure 7. Weed cover and soil mineral N at the vineyard field site.** Mean percentage weed cover (—●—) and $NH_4^+$+$NO_3^-$ ( —×— ) a) in-row strip tillage treatment, b) herbicide treatment. Bars indicate standard error of the mean in mineral N at 95% confidence.

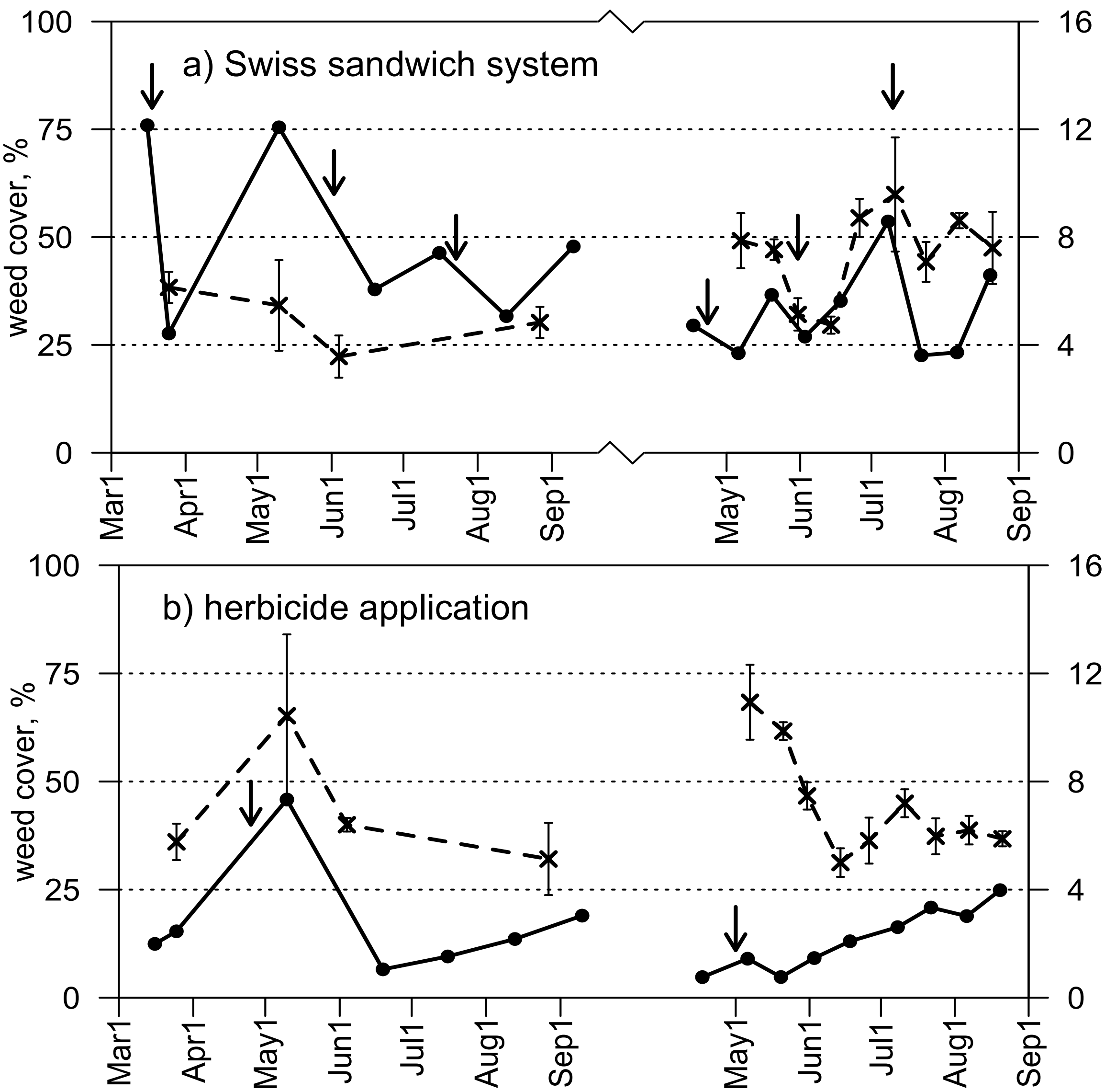


**Figure 8. Weed cover and soil mineral N at the orchard field site.** Mean percentage weed cover (—●—) and $NH_4^+$+$NO_3^-$ ( —×— ). a) Swiss sandwich treatment, b) herbicide treatment. Bars indicate standard error of the mean in the mineral N curves at 95% confidence.

**Table 1. Summary of weed cover analysis.** Taken over two years at two field sites investigating differences between floor management treatment. Tmt = floor management treatment: IRST = in-row strip tillage, SSS = Swiss sandwich system, herb. = herbicide regimen. Mean ± std. err. (95% conf.) listed for mean weed cover change in treated vs. untreated cultivation (SSS and IRST) vs. herbicide plots, spatial var/mean ratios, and temporal variability measured by |change over all periods|. Stars indicate significant difference (α = 0.05) between paired floor management treatments at that field site / year combination, in each of three separate ANOVA models.

| Field site | Tmt. | Treated | Untreated | Var/mean ratio | All periods |
|---|---|---|---|---|---|
| vineyard 2012 | IRST | -8.1±0.3* | +7.6±0.3* | 9.9±0.5* | 15.4±1.5 |
| | herb. | -14.1±0.6* | +3.2±0.4* | 13.2±0.6* | 29.1±1.9 |
| vineyard 2013 | IRST | -6.3±0.3* | +2.6±0.2* | 10.3±0.6 | 12.1±1.1 |
| | herb. | -12.9±0.4* | +3.9±0.3* | 14.2±1.3 | 8.9±0.8 |
| orchard 2012 | SSS | -33.5±0.6* | +24.2±0.5* | 14.2±1.1* | 12.1±1.1* |
| | herb. | -30.5±0.5* | -4.8±0.5* | 19.4±1.1* | 8.9±0.8* |
| orchard 2013 | SSS | -15.7±0.4* | +11.8±0.4* | 13.1±0.6* | 8.2±1.0 |
| | herb. | +4.3±0.2* | +2.3±0.3* | 23.0±1.9* | 7.1±0.6 |

**Soil Nitrogen**

Mean mineral N content of 2013 soil samples decreased over most sampling periods, except those taken 2-4 weeks after a cultivation event at both sites, plus 0-2 weeks after a cultivation event and 4-6 weeks after herbicide application at the vineyard field site (Table 2, Figures 7 and 8). Whole-season mineral N content was not consistently higher or lower in one ground cover treatment or the other.

**Table 2. Summary of soil mineral N results.** Mean ± std. err. (95% conf.) of change in mineral N ($NO_3^-$,ppm + $NH_4^+$,ppm) in floor management trials, by length after a treatment applied (herbicide application or cultivation event). Positive mean changes with s.e. not overlapping zero are in bold.

| | orchard | | vineyard | |
|---|---|---|---|---|
| time after tmt | SSS | herb. | IRST | herb. |
| 0-2 weeks | -1.46±0.82 | (no data) | **+1.12±0.87** | -0.55±1.50 |
| 2-4 weeks | **+1.72±0.91** | -1.07±0.76 | **+1.66±0.93** | 0.36±1.05 |
| 4-6 weeks | -0.83±0.81 | -2.42±0.26 | -0.52±1.7 | **+1.53±1.10** |

**Leaf and Petiole Nitrogen, Apple Yield, and Damage Evaluations**

I detected no difference in the leaf and petiole N content between the herbicide and cultivation treatments, at either site (Figure 9). For the vineyard site, the mean was 0.93±0.05% for cultivation and 1.07±0.08% for herbicide ($t$ = 1.21, $d.f.$ = 3.3, $p$=0.31). For the orchard site, the mean was 1.895±0.135% for cultivation and 2.00±0.07% for herbicide ($t$ = 0.67, $d.f.$ = 4.6, $p$=0.54).

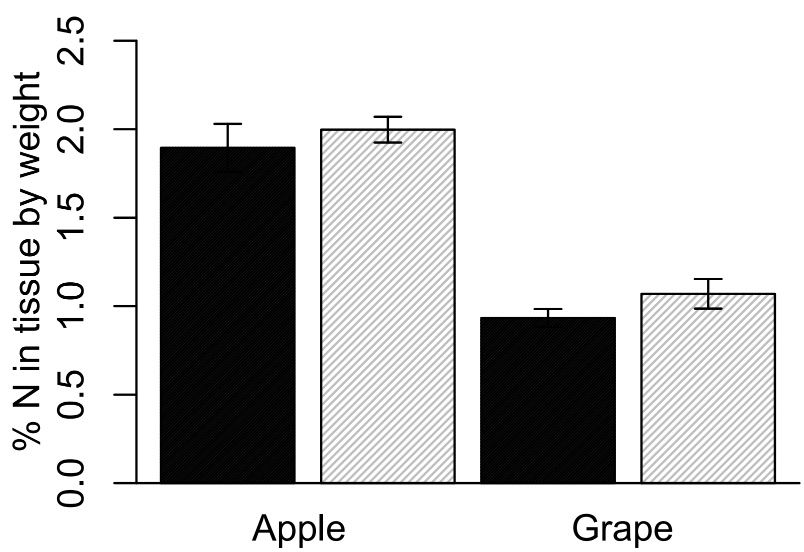


**Figure 9. Leaf and petiole N** in cultivated (■ ) versus herbicide-treated (□) plots, as mean percent N by dry weight. Bars indicate standard error of the mean at 95% confidence.

The mean of 2013 estimated Red Delicious yields were 56.1±4.3 kg per tree for the cultivated rows and 48.4±4.6 kg per tree for the herbicide rows ($t$ = 1.21, $d.f.$ = 57.8, $p$ = 0.23).

**Soil Organic Matter**

No differences in soil organic matter were detected between treatments at either field site ($t$ = 0, $d.f.$ = 15.2, $p$ = 1 for the vineyard site; $t$ = 0.20, $d.f.$ = 13.9, $p$ = 0.85 for the orchard site) (Figure 10).

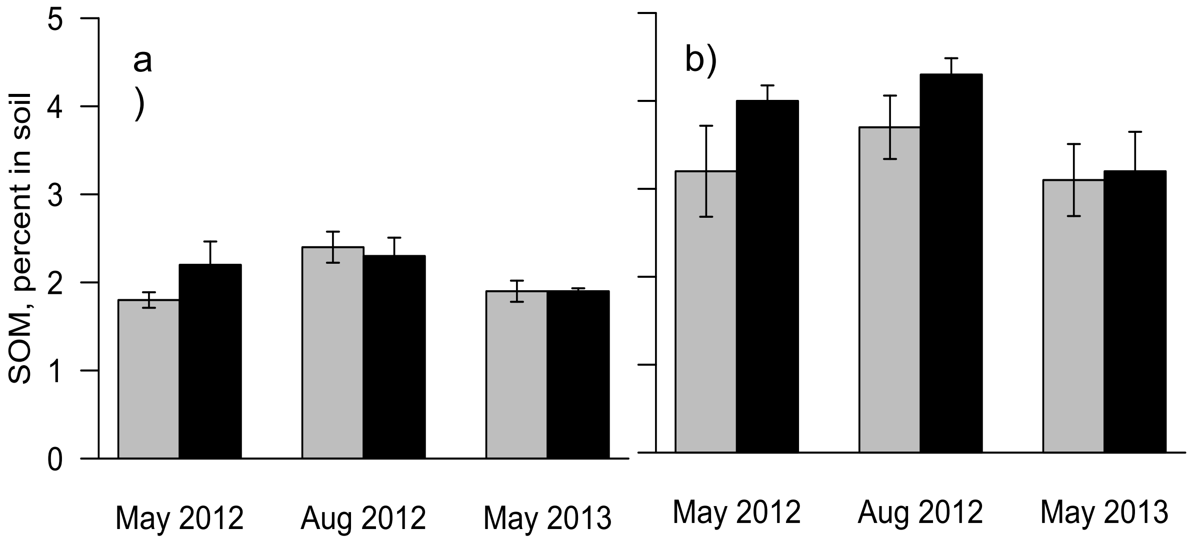


**Figure 10. Soil organic matter**. Mean %SOM ± standard error (95% conf.) between two floor management treatments, strip cultivation ( ■ ) and herbicide application ( ▢ ) at two field sites over three sampling dates. a) Vineyard field site on Emmet sandy loam using In-row strip tillage as a cultivation treatment; b) Orchard field site varying between Capac and Marlette loam, using the Swiss sandwich system as a cultivation treatment.

**Natural Enemy Trapping**

Observed numerical differences in pitfall trap catch between floor management treatments varied depending on the taxon, site, and year. All treatment and treatment*date effects other than those listed in Table 3 below were non-significant at α=0.10. Significant differences at the orchard site 2012 had higher means for cultivation. The significant difference at the vineyard site 2012 (for the earwigs) showed higher activity-density in the herbicide treatment.

**Table 3. Results of ground predator ANOVA.** Fifteen ANOVA models were constructed using pitfall trap catch as the response variable, ground cover treatment (cultivation or herbicide) as a fixed variable, and sampling date and plot as random variables. Four returned significant (<0.10) values for treatment. They are listed below, with their respective *p*-values and treatment means ± std. error.

| Site | Year | Taxonomic group | Treatment effect *p*-value | Cultivation mean±SEM | Herbicide mean±SEM |
|---|---|---|---|---|---|
| Vineyard | 2012 | Forficulidae | 0.059 | 5.8±1.3 | 20.6±5.6 |
| Orchard | 2012 | Carabidae | 0.028 | 3.1±0.7 | 1.5±0.3 |
| Orchard | 2012 | Lampyridae | 0.011 | 2.7±0.6 | 1.3±0.4 |
| Orchard | 2012 | Formicidae | 0.065 | 20.3±3.3 | 11.2±2.1 |

Of the 21 mixed models constructed regressing ground predator catch against weed cover, five returned a significant p-value (Table 4). Of these, three had a positive slope (=mean change in ground predator catch per percentage point of weed cover increase) and two had a negative slope.

**Table 4. Results of ground predator regression vs. weed cover.** Of 21 mixed-model regression of ground predator catch against percent weed cover during trapping period, using experimental plot as a random factor, five returned significant p-values for slope. These models are listed below along with their respective *p*-values, intercepts, and slopes.

| Taxa | Site | Year | p-value | intercept | slope |
|---|---|---|---|---|---|
| Aranae | Vineyard | 2013 | <0.001 | 0.367 | +0.046 |
| Opiliones | Vineyard | 2013 | <0.001 | 1.010 | -0.041 |
| Carabidae | Orchard | 2012 | <0.001 | 0.487 | +0.017 |
| Lampyridae | Orchard | 2012 | 0.005 | 0.334 | +0.014 |
| Aranae | Orchard | 2013 | 0.044 | 1.212 | -0.019 |

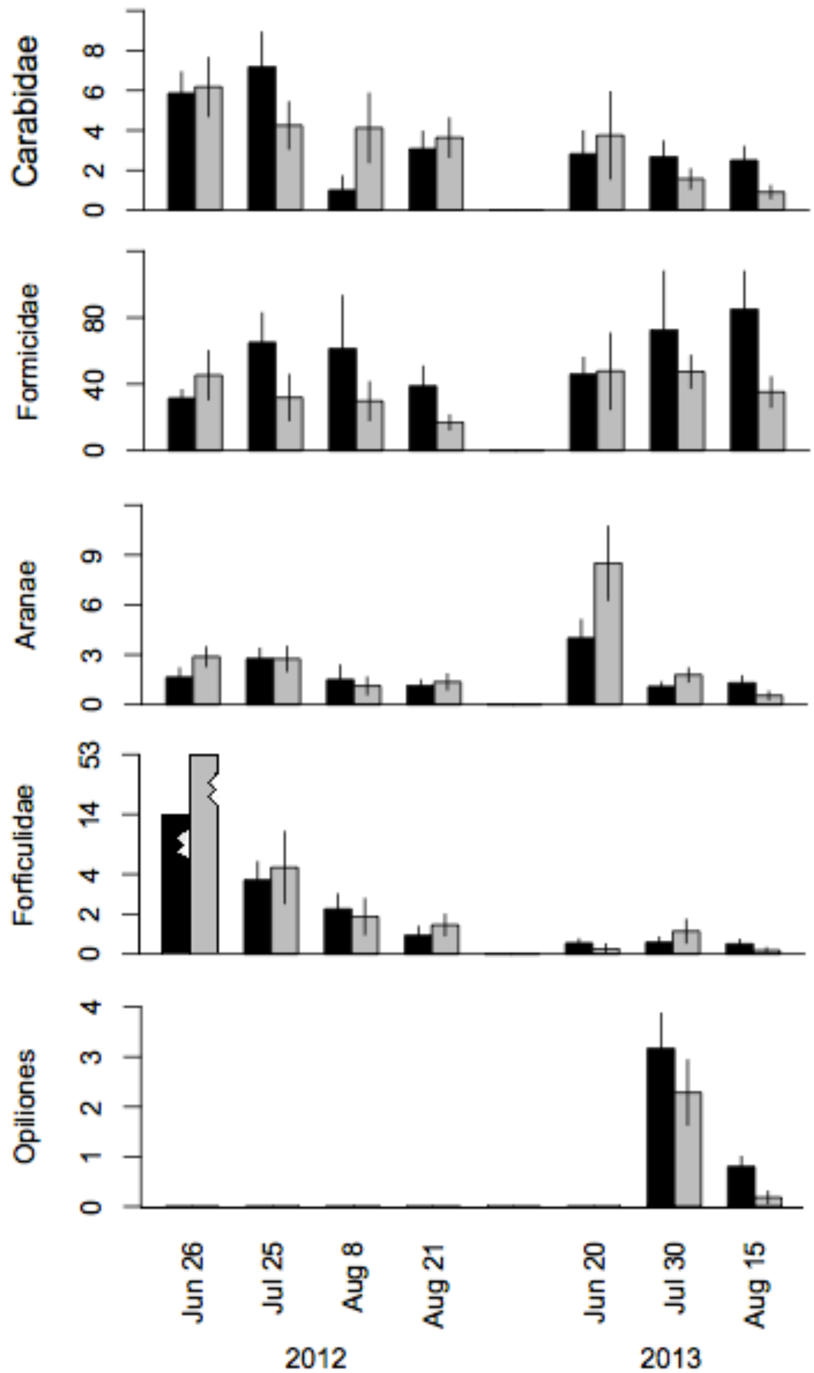


**Figure 11. Ground predator catch at the vineyard site.** Comparing floor management treatments (■ = In-row strip tillage, □ = Herbicide application). Carabidae (ground beetles), Formicidae (ants), Aranae (spiders), Forficulidae (earwigs), and Opiliones (harvestmen) had the highest catch at this site, and are represented in the plots. Bar height is mean catch per trap, and vertical lines indicate standard error of the mean (95% conf.). Note that vertical scales differ between plots, and broken axis for the Forficulidae.

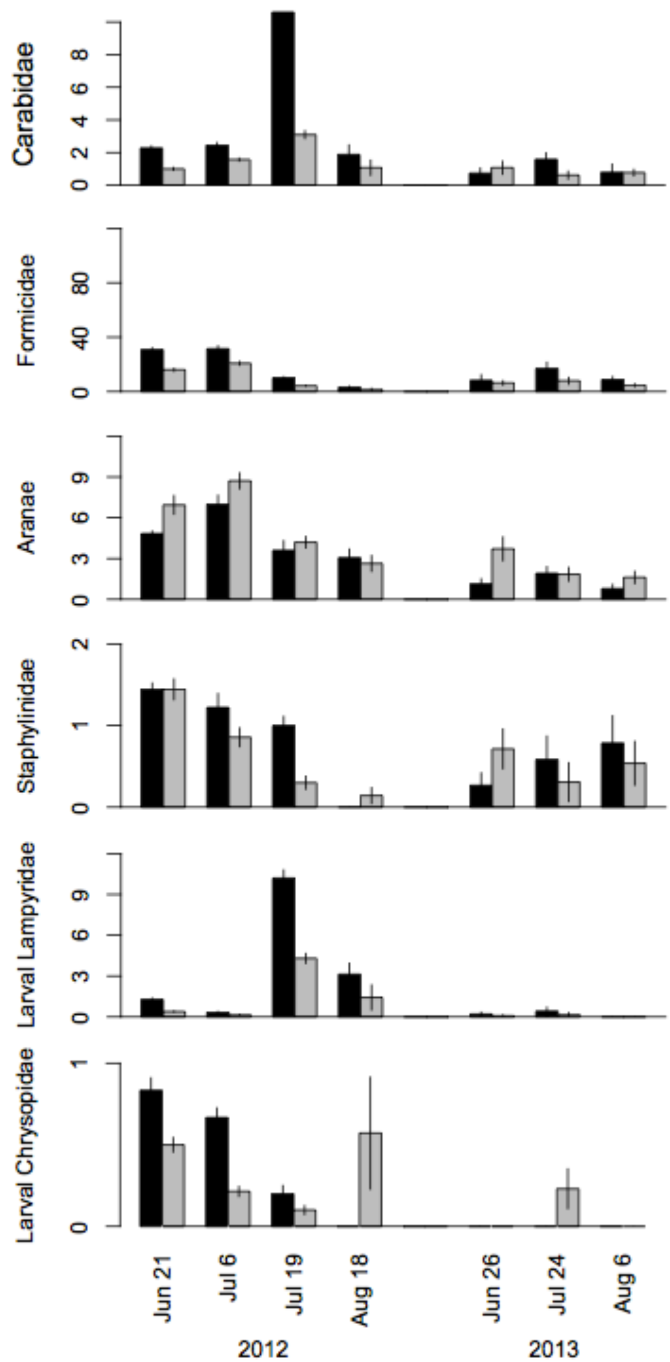


**Figure 12. Ground predator catch at the orchard site**. Comparing floor management treatments ( = Swiss sandwich system, = Herbicide application). Carabidae (ground beetles), Formicidae (ants), Aranae (spiders), Staphylinidae (rove beetles), larval Lampyridae (fireflies), and larvae Chrysopidae (lacewings) had the highest catch at this site, and are represented in the plots. Bar height in mean catch per trap, and vertical lines indicate standard error of the mean (conf. = 95%). Note that vertical scales differ between plots.

### Prey Removal

After one day of being left in the orchard in the two ground cover treatments, 4.0% more eggs were removed in the herbicide treatment than the cultivation treatment (Figure 13). After two days, there were 5.8% more eggs removed total in the herbicide treatment than in the cultivation treatment. By day three, there were 1.8% more eggs removed from the cultivation treatment. A Chi-Squared analysis using the proportion of eggs removed on each day, and the eggs remaining at the end of the experiments, reveals a highly significant difference in the number of eggs removed between treatments (*d.f.*=3, $X^2$=21.7,

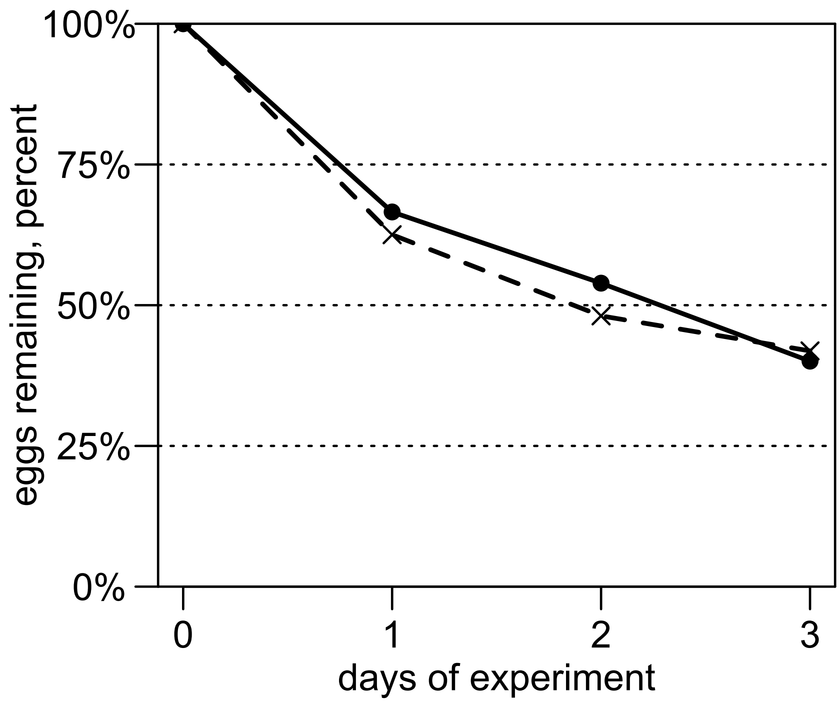


**Figure 13. Sentinel egg removal.** Percentage of original *Heliothis virescens* eggs remaining on cards left in orchard rows for three days for comparison between floor management treatments: Swiss sandwich system (—●—) and herbicide application ( —×— ), total over four runs of the experiment.

$p$<0.01). Conversely, a Chi-Squared analysis using only the proportion of eggs remaining versus removed by the end of the experiment indicates no difference between treatments (*d.f.*=1, $X^2$ = 0.19, $p$=0.67).

**Insect Damage Evaluations**

Apple insect damage in 2013 was very low in all plots, and did not show any significant differences between treatments. For the herbicide treatment, 0.46±0.46% of fruit had tortricid stings, 0.66±0.17% had plum curculio stings, and 0% had tortricid entry wounds. For the cultivation treatment, 0.20±0.12% had tortricid stings, 0.66±0.07% had plum curculio stings, and 0% had tortricid entry wounds.

## Discussion

The assumption that a clean-looking understory is a good understory, and an insistence on keeping the ground bare in the rows throughout the growing season, are common amongst temperate perennial fruit growers. The results from these experiments indicate that this is not always ideal. In regards to available soil N, leaf N, soil organic matter, and natural enemy populations, a continually-rebounding weed cover kept in check with strip cultivation creates an environment that is remarkably similar to that found under a more bare herbicide strip.

As expected, percentage weed cover decreased during treated periods and increased during untreated periods in both floor management tactics, showing that both herbicide application and cultivation are effective at reducing weed pressure. The higher spatial variance:mean ratios in the herbicide treatment indicate that the herbicide weed control was less consistent *spatially* than in the cultivation treatment. There was more variation in percent weed cover over time in the cultivation treatment in one of the four experiments, indicating less consistency *temporally*. Greater spatial variation in the herbicide treatment indicates slightly different levels of weed control, either due to varying susceptibility of different weed species to herbicides, or spotty coverage with the sprayer used. Greater temporal variation in cultivation treatments confirm the hypothesis of a continually rebounding weed cover in that ground management strategy.

Mineral N results from the two treatments were comparable (Figures 7 and 8); available N was not at consistently higher or lower concentrations in one treatment or the other. Leaf and petiole N results were also similar between the two treatments (Figure 9) despite the differences in weed cover. This is in contrast to research reviewed by Hogue and Neilsen (1987), where higher N content was found in apple leaves under cultivation treatment. Conclusions could not be drawn from differences in yield measurements due to differences in management histories between plots.

Cultivation can also be used to quickly release stored N in either ground cover plants or soil organic matter. There was an increase in mineral N content in the cultivation plots 2-4 weeks following a cultivation event (Figures 7 and 8, Table 2), but the increase in mineral N after application of herbicides was slower. Thus, cultivation can be utilized by growers attempting to make stored organic N available to the crop during peak N uptake (Hogue and Neilsen 1987, Guerra and Steenwerth 2012). In apples, N uptake for use in fruit is during the spring, whereas uptake for vegetative growth is later in the season (Ter Avest et al. 2010); therefore an orchardist choosing to cultivate more frequently during this time will make more N available for the current year's crop, increasing yield. Timing of uptake for use in fruit is less clear in grape vines, but probably proceeds from shortly before bloom until veraison (Hanson and Howell 1995, Conradie 1986).

It is not always desirable to increase N availability to grape vines. Fruit quality parameters will increase, and yield decrease, with less available water and N (Amiri and Fallahi 2007). Therefore allowing weeds to return, creating competition to reduce available N and water, can be useful for improving grapes destined for wine making (Guerra and Steenwerth 2012).

Cultivation is also useful for incorporating organic residues. Soil N results from the vineyard 2012 (Figure 7) follow an application of poultry manure compost. Faster N mineralization from the compost appears to occur in the cultivation treatment - i.e. an incorporated organic N source mineralized faster than an unincorporated one. Yet, no differences were found in organic matter content between the two treatments. Changes in soil organic matter content tend to develop over longer time periods than this study encompassed (e.g. Merwin et al. 1994). For example, Zoppolo et al. (2011) saw an increase in soil organic matter in apple orchards where a Swiss sandwich system was maintained with ground-driven implements for four years.

Ground predator populations were also found to be very similar between the two treatments. The exception was the orchard field site in 2012, when greater numbers of ground beetles, ants, and firefly larvae were caught in pitfall traps in the cultivation treatment than the herbicide treatment. This difference could be attributable to a combination of the increased ground cover in the cultivation treatment and the extremely hot, dry weather of 2012. Weeds may have provided shelter to these beneficial insects that was unavailable in the cleaner herbicide plots.

Studies on the relationship between weed cover and natural enemy abundance have yielded positive results. Powell et al. (1985) found that most species of predatory beetles present in winter wheat were more abundant in plots with weed cover left than in plots kept entirely clear. Penagos et al (2003) showed a greater abundance of natural enemies of the fall armyworm, a pest of field corn, and reduced armyworm abundace, where weed cover was allowed to grow, and no difference in yield. In citrus, one weed species was found which, when abundant, fostered a diverse natural enemy community, which in turn decreased populations of the red citrus mite (Liang and Huang 1994). Greater ground cover was also associated with more abundant spiders, predatory hemipterans, and parasitoids in olive orchards (Paredes et al. 2013).

Conversely, for some pests in some habitats, more vegetative cover provides a better habitat for the pest, or a worse one for their natural enemies: Aguyoh et al. (2004) demonstrated this for bean leaf beetle in snap beans. In blueberries, greater damage from Japanese beetles occurred with cover crops than those kept bare of ground vegetation (Szendrei and Isaacs 2005). It is unwise to make generalizations about habitat management impact on pests, predators, or parasitoids. Each arthropod taxon and environment is different, and therefore must be evaluated separately. In our case, the regressions of natural enemy catch against percent weed cover revealed a correlation for several ground predator taxa: harvestmen catch was negatively correlated with percent weed cover, firefly larvae and ground beetles were positively correlated with weed cover, and spiders were positively and negatively correlated in the vineyard and orchard field sites, respectively. These relationships don't yield easily to predictions of weed cover impact on pest insect management.

The prey removal experiments were intended to assess predator complex services directly using a substitute sentinel prey. When checked, the prey removal units most commonly had 0-2 of the 10-20 eggs removed, or 0-2 remaining; units containing intermediate numbers of eggs were rare. From this trend I conclude that, once predators located the eggs, they consumed most or all of them within a 24 hour period. Further, the results of the Chi-squared in the 3-day analysis indicates that predators in the herbicide treatment were able to locate the prey items faster within the three-day window, but by the end of three days the treatments had equalled out: therefore pest management services offered by ground predators were equivalent between the two treatments by the end of the sampling period.

A number of studies have assessed differences in natural enemy populations with varying ground cover in agricultural environments. Whether there is a difference, and whether it affects pest management, seems to depend on a number of factors, probably including the crop, pest, and climate. These results indicate that, except possibly in very dry weather conditions, allowing more weed cover in a conventionally-managed orchard or vineyard in a wet temperate climate will not significantly increase native biocontrol of insect pests.

Given the similarity of weed cover, soil N, leaf N, natural enemies, and organic matter results between treatments, herbicide application and strip cultivation appear to be ground floor management strategies that create very similar soil and insect environments for the crop. An important question for growers is whether the two techniques are similar in cost. A summary of a simple accounting example including chemical inputs, labor, tractor depreciation, fuel, and implement depreciation is below in Table 5.

The use of post-emergent herbicides is similar in cost to the use of a Lilliston-style cultivator like the Wonder Weeder ®, with pre-emergent herbicide application being roughly twice the cost, and radius hoe four times the cost. This shows that strip cultivation and herbicide application can be similarly affordable,

**Table 5. Cost estimates of floor management tactics**, per acre per year. Assumes 100 acre orchard, 50hp tractor, and 5 year old sprayer or cultivating implement. Wonder-weeder estimates apply to any similarly-priced implement being run at 4mph; radius hoe estimates apply to any similarly-priced implement being run at 1.5mph.

| | Cultivation | | Herbicide | |
|---|---|---|---|---|
| | Wonder weeder | Radius hoe | Post-emergent | Pre-emergent |
| Chemical inputs | 0 | 0 | 22.23 | 118.56 |
| Labor | 29.64 | 148.2 | 11.12 | 7.41 |
| Tractor deprec. + fuel | 32.11 | 86.45 | 14.82 | 9.88 |
| Implement deprec. | 15.80 | 41.99 | 14.82 | 9.88 |
| **Total** | **$77.56** | **$276.64** | **$62.99** | **$145.73** |

as long as the cultivator being used can be run at a speed sufficient to keep labor costs low.

In conclusion, strip cultivation and herbicide application created a similar environment to one another for both grape vines and apple trees. In situations like the example above where they are similarly affordable, they can be used nearly interchangeably, with the following exceptions: Both weed control and N mineralization are achieved more quickly with cultivation than with herbicides, yielding an immediate response in weed knockback and only 2-4 week delay in N mineralization. Secondly, the continually-rebounding weed cover offered by strip cultivation may offer shady refuge for beneficial insect predators in dry weather. And thirdly, the monetary costs of strip cultivation are in tractor time and depreciation, whereas the monetary costs of herbicides are in chemical purchases.

## CHAPTER THREE: CULTIVATION FOR ORCHARD INSECT PEST MANAGEMENT

### Introduction

Strip cultivation is a weed management strategy used in perennial fruit crops wherein drive rows are in grass or mixed vegetation and mowed, while a strip on each side of the tree rows is cultivated (Weibel 2002). When accomplished using a shallow, ground-driven implement, strip cultivation is used to reduce weed competition with the crop, while allowing weeds to regrow and retain soil nutrients and organic matter (Peck et al. 2011, Zoppolo et al. 2011).

Strip cultivation may also negatively affect insect pest populations. Cultivation is used for insect pest management in annual crops, where the presence of bare soil at least once a year affords an opportunity to affect pest populations with soil disturbance (Stinner and House 1990). For example in cotton, tillage is a commonly-used management strategy for bollworms, *Pectinophora gossypiella* (Lepidoptera: Gelichiidae), as well as white grubs, termites, and scale insects (Chu et al. 1996, Russell 2004). In maize, plowing under the residue has been shown to make it unavailable as an overwintering site for black cutworm (Lepidoptera: Noctuidae, *Agrotis Ipsilon* Hufnagel) (Johnson et al. 1984, Willson and Eisley 1992). In trials in both peanuts and sweet potatoes, tillage can reduce wireworm (Coleoptera: Elateridae) damage (Scarpellini et al. 2004, Seal et al. 1992). Unfortunately, research on cultural control tactics such as cultivation lacks the economic incentive offered by research centered on product development, so proportionately less research is done to address cultivation (Dent 2000).

There are limited examples of similar management recommendations in perennial fruit. Throwing up a furrow onto the vinerows was at one time recommended as a means of Grape Berry Moth (Lepidoptera: Tortricidae: *Paralobesia viteana* Clemens) control, and some rudimentary trials indicated that emerging adults are unable to dig upwards through an inch or two of soil (Isely 1917). Conversely, work with codling moth showed that they are capable of digging out of six inches of soil (Steiner 1929). Soil mounding has also been found to be an effective control measure for the dogwood borer, *Synanthedon scitula* (Gut et al. 2005). Beyond these studies, little has been done to address the question of insect pest management using cultivation in perennial fruit. Thus, we undertook a study to determine the direct impact of strip cultivation on insect pests of apple.

Apples have a diverse community of pest insects (Slingerland and Crosby 1914). Two of the pests of greatest economic importance in the Eastern United States are the plum curculio, *Conotrachelus nenuphar* Herbst (Coleoptera: Curculionidae) and the codling moth, *Cydia pomonella* L. (Lepidoptera: Tortricidae). Plum curculio adults feed and lay eggs in developing apples, larvae tunnel inside fruit, pupate in the soil after June drop, then emerge as adults to feed on mature fruit (Quaintance and Jenne 1912, Paradis 1957, Lan et al. 2004). Plum curculio can be targeted with a cultivator when the larvae are still feeding in excised apples on the ground, and after larvae bury themselves to pupate. Codling moth lay eggs on the surface of developing fruit in the spring. Larvae enter and feed inside fruit, and exit fruit to seek a pupation site either on the tree or, if no sheltered cracks are available from bark or pruning wounds, in the leaf litter on the ground (Geier 1963, Blomefield and Giliomee 2012). Second-generation codling moth diapause as larvae in the fall, at which time those that have chosen a diapause site on the ground can be targeted by cultivation. The ground-diapausing portion of the population is greater in orchards with smoother-barked trees (Slingerland 1898, Crosby and Leonard 1914).

This study focused on how the application of strip cultivation affects the survivorship of codling moth and plum curculio. Our two experimental objectives were to determine: a) the burial, mechanical damage, and burial depth of sentinel plum curculio-infested apples and cocooned codling moth, and b.) determine the survival of plum curculio and codling moth buried at variable depths in a controlled laboratory environment.

## Materials and Methods

### Insect Culture

Adult plum curculio were collected from a colony maintained by the Pesticide Alternatives Laboratory, Michigan State University, East Lansing, MI. Weevils for this colony were collected from Benzie, Ionia, Leelanau, and Manistee Counties, Michigan. In this colony, adults are held in cages containing thinning apples treated with a plant growth regulator (Diphenylamine) and two fungicides (Captan 80 WDG and Benlate 50W) and rinsed. They are then treated with pyriproxyfen (Esteem® 35 WP, 750.0 mg/ L water) in order to break the obligate diapause, inducing oviposition. Infested apples are transferred to the surface of a soil medium for larval development and pupation to adulthood.

After acquiring the adults, we placed fifty thinning apples in each of a number of mesh bags. We sexed the plum curculio using the shape of the first ventral abdominal segment under a dissecting microscope, according to Thomson (1932). We then carefully placed four females and two males into each bag with the apples. After 20 days, we assessed plum curculio infestation by removing and dissecting 5 apples from each bag. We found that the plum curculio were completing their development as larvae, and began experiments. In rearing for the field experiments, we began with 50 bags, and the 25 bags containing the greatest number of plum curculio in the assessed apples were used for the experiments. In rearing for the lab experiments, we began with 10 bags, and used the five containing the greatest number of larvae for the experiments.

Codling moth pupae for the field experiments were ordered and shipped from the USDA Yakama Agricultural Research Lab.

For lab experiments, codling moth eggs were acquired from the colony at the Trevor Nichols Research Station at Michigan State University. The eggs we acquired were laid on a piece of wax paper. We submerged them in a 100:1 dilution of bleach in water for 30 seconds to prevent fungal growth. The neonates began to hatch several days later. We removed the neonates one at a time with a small wet paintbrush and placed them each in a separate diet cup containing a recently-poured and dried codling moth diet. Each batch of diet consisted of 213 g organic pinto bean powder, 20 g agar, 3.2 g ascorbic acid, 32 g brewers' yeast, 1 g Fabco, 2 g methyl paraben, 1 g sorbic acid, and 4 Vanderzandt Vitamin. All ingredients were acquired from Bioserve (Beltsville, MD), except the Pinto beans, which came from a grocer. Diet cups with larvae were kept at 25$^{O}$C and 45% humidity with a 16hr:8hr light:dark cycle for the first codling moth experiment, and 20$^{O}$C and 75% humidity with a 16hr:8hr light:dark cycle for the second.

**Field Experiments**

For the field experiments, we used apples infested with plum curculio (method above), and a simulated leaf litter containing cocooned codling moth. Field experiments were conducted at a commercial organic apple orchard with mature trees, located near Flushing MI, USA (N43.0274, W83.9133). The orchard is situated on flat land, on a heavy clay soil.

Our experimental plots consisted of a 1m x 2m section within the cultivated area of the orchard floor, positioned 15 m away from each other within the row. We performed two separate experiments, one with plum curculio and the other with codling moth.

For the plum curculio experiment, 50 infested apples were spread evenly over each plot - 2 apples were picked at random from each of the 25 rearing bags used. 10 plots received the cultivation treatment, and 10 received the control treatment.

For the codling moth experiment, pupae were carefully placed within a 1.5 x 2.0 cm tube of orange label tape containing a Zinc #8-32 nut. The label tape served as an artificial pupation site and both the color and nut helped in retrieval after cultivation. Sixty of these were spread out evenly on the ground within each experimental plot. Eight plots received the cultivation treatment, and eight received the control treatment.

In both experiments, our grower collaborator made two passes in the cultivation treatments, with a custom-built Lilliston style (spider tines) cultivator (Figure 4). After cultivation, the apples and tape rolls were retrieved from both treatments with a rake and hand digging, and additionally with a metal detector in the codling moth experiment. We counted and recorded the percent recovered, percent damaged, and percent buried, and we estimated the depth of burial visually. Codling moth pupae were evaluated in the laboratory for mechanical injury.

**Laboratory Experiments**

Plum curculio and codling moth survival and development after burial was assessed at a range of depths in custom-built burial arenas. The experimental arenas consisted of 15-cm diameter PVC tubes oriented vertically. They were cut to lengths that provided 7.5 cm of soil medium below the buried insects and 7.5 cm of air space above the level of soil. The total height of arenas used for plum curculio were: 15, 17.5, 22.5, 30, and 60 cm - with 0, 2.5, 7.5, 15, and 45 cm corresponding burial depths. The total heights of arenas for the codling moth experiment were: 15, 16, 17.5, 22.5, and 37.5 cm - with 0, 1, 2.5, 7.5 and 22.5

cm corresponding burial depths. Commercial shear fabric was attached across arena bottoms with hot glue. Burial proceeded as follows: we added 7.5 cm of soil medium to the arena, spread the insects out in a layer, and covered them with the treatment depth of soil medium.

For the plum curculio experiment, five infested apples, one from each larval rearing bag, were buried in each arena. In the first codling moth experiment, codling moth diet discs were buried 30 days after eggs hatched, while they were pupating inside the diet. In the second codling moth experiment, diet discs were buried while they were still developing larvae.

The arena was then covered with a piece of shear fabric affixed using a rubber band so that any emerging insects would not be able to crawl or fly out. We brought the soil medium to field capacity by setting the tubes in a tray of water until moisture appeared at the surface of the medium. Tubes were removed from the water and set in a dry environment for the duration of the experiment. They were checked every 4-5 days for emergence. Larvae and pupae found to have emerged were not removed from the arenas, to assess whether they would complete their development. Adults were removed when counted, and returned to the colony.

**Data Analysis**

Data from laboratory experiments were non-normal. Therefore a Kruskal-Wallis model of emergence against burial depth for the plum curculio experiment (5 levels), and a Kruskal-Wallis model of emergence against burial depth *and life* *stage* for the second codling moth emergence (5 x 2 levels) were used followed by Wilcoxon pairwise comparisons when the overall model was significant.

## Results

### Field Experiments

Recovery after cultivation was 91.7±3.1% from plum curculio infested thinning apples and 86.8±2.2% from codling moth litter (Figure 14). Field burial with the Lilliston-style cultivator was 61.3±1.4% for plum curculio and 83.1±2.9% for codling moth. Mechanical injury to codling moth was 7.5±1.6%, and damage to infested apples was 14.9±1.9%. Depth of burial ranged between 0 and 7 cm for both apples and artificial litter.

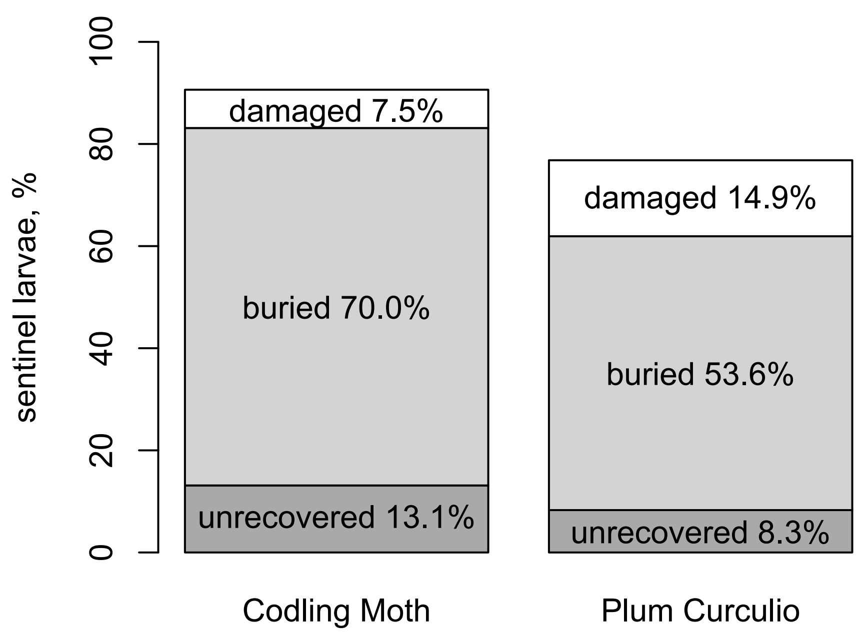


**Figure 14. Field insect burial results.** Percent unrecovered, buried, and physically damaged codling moth litter (left) and plum curculio-infested apples (right) after two passes with a Lilliston cultivator. Data reflect totals across all replicates.

## Lab Experiments

The effect of depth of burial on emergence of plum curculio was highly significant ($\chi^2$ = 15.73, *d.f.* = 4, $p < 0.01$) (Figure 15). Significantly more *C. nenuphar* adults emerged from the 2.5 cm burial than from the surface control ($p$=0.04), and numerically but not significantly more emerged from 7.5cm and 15cm burial ($p$=0.13 and $p$=0.17, respectively). None emerged from 45cm burial.

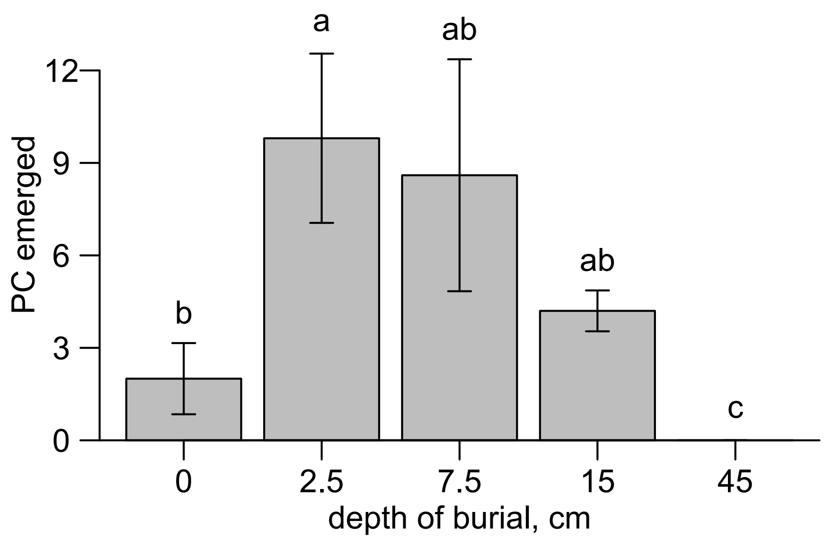


**Figure 15. Lab plum curculio burial results.** Mean (±SEM) emergence per chamber, by depth of burial in wetted sand. Same letters indicate statistical equivalence (α=0.05) in a Wilcoxon rank sum test.

In the first codling moth experiment, where pupae were buried in sand, no *C. pomonella* emerged from any of the burial depths, whereas an average of 50% emerged from the soil surface treatment (Figure 16a). In the second experiment, where mature larvae were buried in potting mix, emergence occurred from various depths, and the effect of depth on emergence was significant ($\chi^2$ = 12.58, *d.f.* = 4, $p$ = 0.01). Significantly more codling moth larvae emerged from the soil surface treatment than the 7.5 and 22.5 cm depths ($p$ = 0.049 and $p$=0.007, respectively) but not the 1 or 2.5 cm burial depth ($p$=0.086

and $p$=0.52, respectively) (Figure 16b). Larvae emerging from burial were generally unable to complete their development to the adult stage (Figure 16b), and the depth effect was significant ($\chi^2$ = 17.17, *d.f.* = 4, $p$ < 0.01). The number of larvae and adults recorded for the surface control and 7.5 cm depth were very similar (surface $p$=0.38; 7.5cm $p$=0.42), whereas fewer adults emerged than larvae unburrowing from the 1cm and 2.5cm depths (1cm $p$=0.07; 2.5cm $p$=0.09).

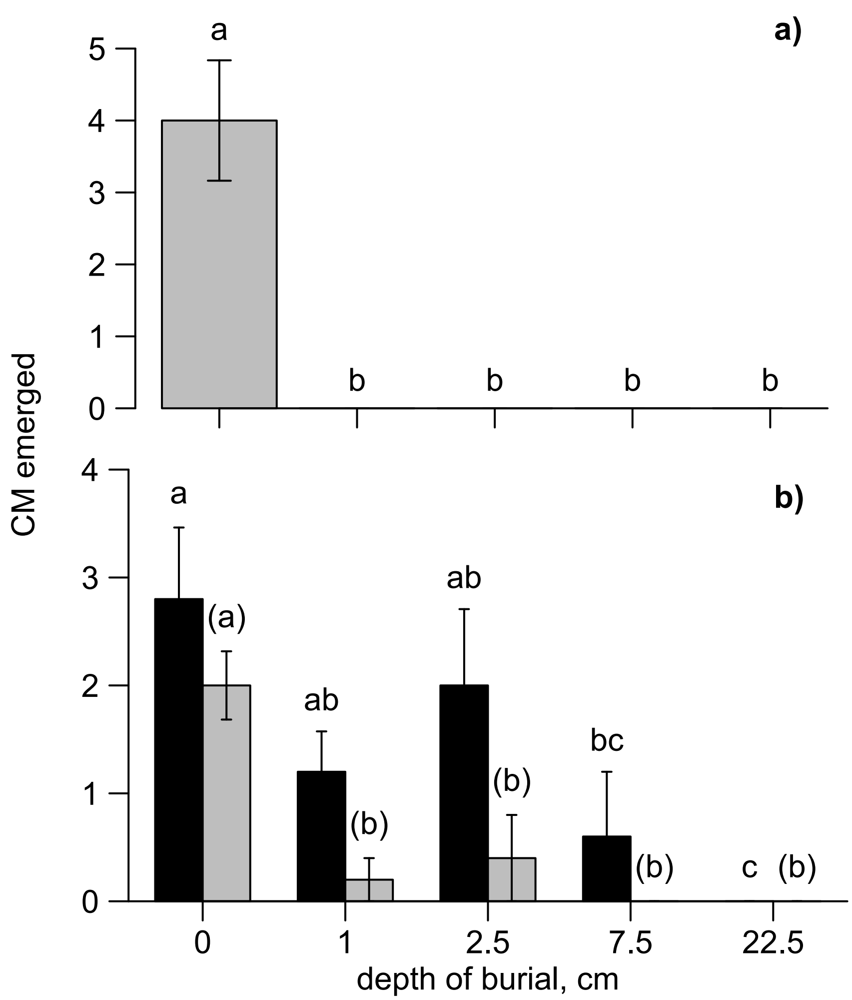


**Figure 16. Lab codling moth burial results.** Mean (±SEM) emergence per chamber, by depth of burial. Mean *adults in grey* and *larvae in black*, emerged per tube. Same letters indicate statistical equivalence in a Wilcoxon rank sum test (α=0.05). **a)** emergence of adult codling moth from sand. **b)** emergence of larval codling moth from potting soil

## Discussion

Two passes with a Lilliston cultivator resulted in 7-15% of sentinel larvae in the cultivated area being mechanically damaged. However, half or more of sentinel larvae in the area were buried, up to 7cm deep. This is consistent with previous studies - cultivation-mediated mortality more typically comes from alteration of habitat than direct mechanical destruction of pests (Stinner and House 1990).

In wetted sand, more *C. nenuphar* were able to emerge from the buried apple treatment than from the surface treatment. These results are somewhat intuitive: plum curculio larvae bury themselves before pupating (Lan et al. 2004), so it is unsurprising that anthropogenically buried larvae would be more likely to recruit successfully into the next generation. These results suggest that mechanical burial is unlikely to provide management of plum curculio. This agrees with previous work with weevil pest species such as *Hypera postica* and *Sitona hispidula* in alfalfa, which are unaffected by tillage (Stinner and House 1990). Conversely, moldboard plow reduced emergence of sunflower seed weevils (*Smicronyx fulvus*) by 29-56% in the field (Gednalske 1984). The moldboard plow is designed to run at a 25-30 cm depth, and this may be less a difference in the physiology of the weevils, and more a difference in depth of burial itself. In our lab experiments, the transition between depths from which the beetles could emerge and depths where they could not, was between 15 and 45 cm.

The increase in adult emergence from burial that was observed in the laboratory may or may not also apply to burial by a cultivator in the field; work using emergence cages over treated patches is needed. If adult emergence is found to increase through burial in the field, then those apple growers using cultivation as a weed management strategy would be at risk of worsening plum curculio pressure if they cultivate after June drop. Further, our lab experiments only addressed mortality by burial alone; field burial may also make insects vulnerable to fungal disease, nematodes, or natural enemy predation (Dent 2004).

In wetted sand, no codling moth adults were able to emerge from burial. Those larvae that were able to emerge from burial in potting soil were largely unable to complete their development to the adult stage. This is in contrast to the results of Steiner (1929), who reported emergence of codling moth from up to six inches of soil. Our results suggest that larval or pupal burial resulting from cultivation events could potentially be a useful management tool for codling moth. Though again, field trials addressing this question directly would be necessary before making this recommendation to apple growers.

Further, the timing and phenology of the two codling moth generations is likely to affect the utility of cultivation as a management tool. The first generation of codling moth pupates over several summer weeks with individuals emerging throughout this period (Reidl and Croft 1978). In contrast, the development of the second generation is arrested as they enter diapause. Thus, if cultivation can reduce codling moth populations, treatments targeting codling moth on the orchard floor are likely to be more effective when focusing on the second generation with passes made in the late fall or early spring.

In summary, there is evidence to suggest that strip cultivation is a management tool for codling moth. This is most practical for growers already running a cultivator through their orchard; accomplishing some weed and pest control with a single tool is desirable. The plum curculio is not negatively affected by burial alone, and in a sterile-sand environment burial actually results in a higher percentage recruitment into the next generation for plum curculio. Codling moth adults, on the other hand, can be killed by burial alone, even under as little as 1 cm of sand. Codling moth larvae are also sensitive to burial, able to burrow out from potting soil but largely unable to complete their development after emerging from the soil. The results from both of these insects merit further study in field environments - is burial also a boon to plum curculio in the field? Is it as effective at reducing populations codling moth in the field? Do these outcomes vary by soil type? Further work is needed before management recommendations can be made to tree fruit growers.

## CHAPTER FOUR: SYNTHESIS AND CONCLUSIONS

There are numerous tools and techniques available for ground management in perennial fruit. These include herbicide strip, cultivation, flame weeding, mulching, cover crops, and grazing. Each technique impacts weed cover, competition for soil water and nutrients, natural enemy habitat, and pest insects, in various ways that depend on climate, soil type, cropping system, and weed species composition (Hogue and Neilsen 1987, Merwin 2003, Guerra and Steenwerth 2012). Therefore, agricultural scientists can only provide context-specific information on the results of the various techniques on different system components, with which growers can make management decisions. This work sought to compare strip cultivation techniques to herbicide application from this research perspective.

### Objective 1: Ground Cover and Soil Properties

Ground cover results from the orchard site show a continually-rebounding weed cover following each cultivation event (Figures 7 and 8). I originally hypothesized that this would allow the accumulation of soil organic matter over the course of the time in which cultivation occurred. However, there was no significant difference in the organic matter content between cultivated and non-cultivated plots (Figure 10). It is likely that several years of data would be needed to properly address this question: Zoppolo et al. (2011) recorded an increase in soil organic matter under the Swiss sandwich system over four years, whereas Hipps and Samuelson (1991) showed a decrease in organic matter under herbicide strip over 14 years. In our study, the small numerical difference is in favor of the cultivation treatment indicates that no organic matter was likely to be lost in the cultivation treatment.  Organic matter content is critical for nutrient and water retention in the soil, particularly in regards to N (Haynes 1986).  On farms attempting to reduce their reliance on inorganic fertilizers and reduce nutrient leaching, increases in soil organic matter content are essential for soil fertility.

Soil mineral N content increased faster in the in-row strip tillage treatment than the herbicide treatment after poultry manure compost addition (Figure 7). Increased N availability due to mineralization was expected after cultivation (Hogue and Neilsen 1987).  The increased sampling frequency in 2013 allowed us to see the increase in mineral N following a cultivation event - there appears to be a two to four week gap between a cultivation event and subsequent N mineralization (Figures 7, 8, Table 2).  This is a rapid mineralization event, for instance in comparison to an incorporated clover cover crop, which takes 4-8 weeks to increase mineral N content of the soil (Francis et al. 1992).  This outcome was expected; most weed species have a low C:N ratio (Lindsey et al. 2013).

Plant levels of N were not different between the two treatments in either crop (Figure 9).  This indicates that strip cultivation in this study had a similar effect in reducing competition with weeds for N as a commercially-typical herbicide strip treatment.  Over the two years of our study, herbicides and strip cultivation provided a similar environment for the crop in reference to soil and weeds, as far as our data indicate.  These conclusions are in accord with Pool et al. (1990), who found no difference in yield, sugar content, or vegetative growth in grape between cultivation and herbicide application. Literature reviewed by Hogue and Neilsen (1987) showed similar results. Yet they are somewhat at odds with conventional practices of ground floor management among perennial fruit growers. Our data indicate that complete elimination of weeds in the understory is unnecessary. For organically-certified perennial fruit growers, cultivation is an option on par with herbicides in its effectiveness.

**Objective 2: Natural Enemy Habitat**

The only significant differences in ground predator catch between floor management treatments were in the earwig population at the vineyard in 2012, where the herbicide treatment had higher catch (Figure 10 and Table 3), and in the orchard 2012, for carabids, ants, and firefly larvae where the cultivation treatment had a higher catch (Figure 11 and Table 3).

Studies on the relationship between weed cover and natural enemy abundance have yielded positive results. Powell et al. (1985) found that most species of predatory beetles present in winter wheat were more abundant in plots with weed cover left than in plots kept entirely clear. Penagos et al. (2003) showed a greater abundance of natural enemies of the fall armyworm, a pest of field corn, and reduced armyworm abundace, where weed cover was allowed to grow, and no difference in yield. In citrus, one weed species was found which, when abundant, fostered a diverse natural enemy community, which in turn decreased populations of the red citrus mite (Liang and Huang 1994). Greater ground cover was also associated with more abundant spiders, predatory hemipterans, and parasitoids in olive orchards.

Conversely, for some pests in some habitats, more vegetative cover provides a better habitat for the pest, or a worse one for their natural enemies: as demonstrated by Aguyoh et al. (2004) for bean leaf beetle in snap beans. In grapes, greater damage from Japanese beetles occurred in vineyards with cover crops than those kept bare of ground vegetation (Szendrei and Isaacs 2005). It is difficult to make generalizations about habitat management impact on pests, predators, or parasitoids. Each arthropod taxon and environment is different, and therefore must be evaluated separately. The regressions performed in this study of natural enemy catch against percent weed cover revealed the following correlations with increased weed cover: increased ground beetle and firefly larval catch, decreased harvestmen catch, and increased or decreased spider catch depending on field site. Without knowing which of these arthropods has the greatest impact on pest insects in our context, these results allow no predictions of the relationship between ground cover and pest insect management.

Despite the differences noted above, proportion of sentinel prey removed by the predator community was remarkably similar between treatments (Figure 13). It should be noted that the prey removal experiments were performed at the orchard in 2013; differences in ground predator catch were observed in 2012, so it would be expected that the outcome between the two treatments would be similar in 2013. However, the rate of removal over the first two days did differ, and was faster in the herbicide treatment. This may be due to the more complex habitat of greater weed cover in the cultivation treatment at that time, meaning that it took predators more time to locate the prey eggs.

It also must be understood that this study was conducted in an environment where repeated insecticide sprays were being used. The fact that there were few significant differences in natural enemy catch and none in total predator activity measured by the sentinel prey may not reflect a lack of difference in suitable habitat, but instead may reflect a dampening of the habitat effect via insecticide sprays. Epstein et al. (2001) showed that ground beetles are severely affected by neural-active insecticides in orchards, so our floor management effects may have been different without insecticide application. Assessing the suitability of a continually-rebounding weed cover like that created by both of the cultivating implements used in this study might be better done in an orchard or vineyard environment where insecticides have not been used for several years, giving the natural enemy community a chance to build up.

**Objective 3: Cultivation as a Pest Management Tool.**

Strip cultivation has the potential to help or hinder in insect pest management by affecting pests directly during soil-dwelling life stages. Field study results indicate that a Lilliston cultivator buries the majority of inactive soil surface larvae, but mechanically damages only 8-15% (Figure 14).

Lab results indicate that burial with a cultivator is not likely to be an effective tool for management of plum curculio - indeed, greater emergence was observed from shallow burial treatments (≤15 cm) than the surface control (Figure 15). This agrees with previous work with weevil pest species such as

*Hypera postica* and *Sitona hispidula* in alfalfa, which are unaffected by tillage (Stinner and House 1990). Deeper burial does have an impact on weevil larvae - none emerged in our trials from the 45 cm burial depth. Gednalske (1984) found that moldboard plow reduced emergence of sunflower seed weevils (*Smicronyx fulvus*) by 29-56% in the field; however, deep plowing is obviously not possible in a perennial fruit environment.

Field trials are needed to address whether increased emergence occurs in the orchard after burial of plum curculio-infested dropped apples. If it does, then cultivation after June drop would risk greater plum curculio damage to fruit for growers using cultivation as a weed management strategy. Even so, some possibility remains that cultivation could be a successful management strategy for plum curculio - there are more sources of mortality from buried plum curculio in the field, including exposure to fungal disease and ground predators (Dolan 2004), which may be altered by burial.

For codling moth, lab results show that adults are unable to escape burial under 1 cm or more of wetted sand (Figure 16a). This is contrary to Steiner (1929), who reported emergence of codling moth from up to 15 cm of loose soil. In the experiment in potting soil, larvae were able to emerge, though these larvae were fewer compared to the unburied control, and very few of them were able to complete their development compared to unburied larvae (Figure 16b). This may be due to cuticular injury while burrowing upwards, or the metabolic cost of excavation.

Based on results for the burial of codling moth, correctly-timed cultivation in the field is likely to be a useful tool for their management, as soil mounding is with dogwood borer (Gut et al. 2005). However, further field experiments will be necessary before recommendations can be made to fruit growers: for instance, using field cages to measure emergence of cultivation-treated sentinel pests in the orchard. Also cultivation's efficacy as a codling moth management tool will depend on a variety of factors. Timing of cultivation is one — cultivation events performed after second-generation larvae begin their diapause in the fall, or before they emerge as adults in the spring, have a higher likelihood of impacting codling moth, while the entire population is synchronously overwintering. Additionally, cultivation is more likely to impact codling moth in orchards where suitable diapausing sites on trees and posts are rare, forcing codling moth to pupate in the less favorable environment of the leaf litter. This would require young trees, or those with dwarfing rootstocks.

## Further Work

We are making the results of this thesis work available to growers through presentations at grower meetings and online seminars. I have also produced an extension bulletin (see Appendix of this thesis) to communicate the results of this research to the grower community. We have been soliciting grower comments and advice on next steps for research, as well as descriptions of individual experience with various techniques and cultivating implements.

This research has generated specific questions for further inquiry by the agricultural science community. Firstly, Carbon to Nitrogen ratios have not been calculated for many common weed species at different developmental stages. Predictions regarding the rate of nitrogen mineralization and immobilization are being developed for sustainable cover crop management. For those growers managing native weed cover (rather than seeded cover crop) with cultivation, mineralization rates based on C:N ratios would be useful for ground management decisions - thereby, more specific cultivation timing could be recommended. Second, to build a record of changes in soil organic matter under different soil conditions and cultivating implements, longer trials are needed; organic matter levels can take years to change appreciably. Third, studies exposing plum curculio and codling moth to cultivation in the field and measuring emergence thereafter are needed to ascertain whether our lab burial results translate to field conditions.

**APPENDIX**

**APPENDIX: DRAFT OF EXTENSION BULLETIN,
"STRIP CULTIVATION IN PERENNIAL FRUIT"
WILLIAM B. BAUGHMAN, MATTHEW P. GRIESHOP**

**Figure A1. Cultivated apple row**

**Figure A2. Herbicide-treated apple row**

Multiple tools and techniques are available for floor management in tree fruit, grapes, and other perennial fruit crops. The herbicide strip is the most commonly-used system. Flame weeders, cultivating implements, cover crops, and mulches are also available for growers interested in reducing herbicide use. Strip cultivation refers to using a shallow tilling implement such as a disk, tooth arrow tiller, rotary hoe, or rotating-tine cultivator to maintain a low- to no-weed strip on both sides of the tree- or vine- rows. Here we will discuss some of the relative benefits and drawbacks of managing weeds with strip cultivation, compared to herbicides, and some results of our research project on cultivation over the past two years. Specifically we address weed cover, soil nitrogen, insect predator community, and pest insect mortality.

**Basics**

Repeated passes over the course of the season are required to achieve sufficient weed control with cultivation. Depending on rainfall, soil type, and which cultivator is being used, this will generally be three to five passes. The implements we discuss here are the Wonder-weeder, which is a Lilliston-style (spider) cultivator, in apples, and the Clemens radius hoe in grapes. Our grape grower collaborators were most comfortable with the radius hoe running at 1-2 mph, which is about 0.5-1 acres/hr for 10ft row spacing. The Wonder-weeder can be run much faster - 3-5 mph, which translates to 1.5-2.5 acres/hr for 10ft row spacing. Depending on which herbicides and cultivating implements are being compared, and whether you have the infrastructure to fabricate your own, strip cultivation may be cheaper or more expensive on a per acre basis than

**Figure A3. Wonder-weeder in use**

**Figure A4. Radius hoe**

**Figure A5. Radius hoe in use**

herbicide application (Table A1, below). Fabricating a spider tines implement is fairly straightforward; individual spider gangs are available from Bingham Ag if they can't be found locally.

**Table A1. Cost estimates of floor management tactics**, per acre per year. Assumes 100 acre orchard, 50hp tractor, and 5 year old sprayer or cultivating implement. Wonder-weeder estimates apply to any similarly-priced implement being run at 4mph; radius hoe estimates apply to any similarly-priced implement being run at 1.5mph.

| | Cultivation | | Herbicide | |
|---|---|---|---|---|
| | Wonder weeder | Radius hoe | Post-emergent | Pre-emergent |
| Chemical inputs | 0.00 | 0.00 | 9.00 | 48.00 |
| Labor | 12.00 | 60.00 | 4.50 | 3.00 |
| Tractor deprec. + fuel | 13.00 | 35.00 | 6.00 | 4.00 |
| Implement deprec. | 6.40 | 17.00 | 6.00 | 4.00 |
| Total | $31.40 | $112.00 | $25.50 | $59.00 |

**Ground cover and soil nutrients**

We measured percent weed cover, soil nitrogen, and leaf nitrogen over the course of two years at one vineyard and one orchard site, comparing strip cultivation in some plots with herbicide application in others.

Tree- or vine-rows weren't as clean looking as herbicide rows with either of these implements (Figure 6A, next page). However, sufficient weed control was achieved that crop plants experienced similar nitrogen conditions in cultivation and herbicide plots, indicated by soil- and leaf nutrient results. We also observed an increase in available nitrogen in the soil 2-4 weeks after each pass, when organic nitrogen broke down and became accessible to crop (Figure 6A, next page).

We also measured changes in soil organic matter content over the course of the study. Over two years, there was not a significant change in organic matter, but there was slightly more in the cultivation plots compared to the herbicide plots. Using a shallow-ground driven cultivator (as opposed to PTO-driven) reduces the chance that organic matter will be lost from repeated passes, as long as weeds are given time to recover between passes.

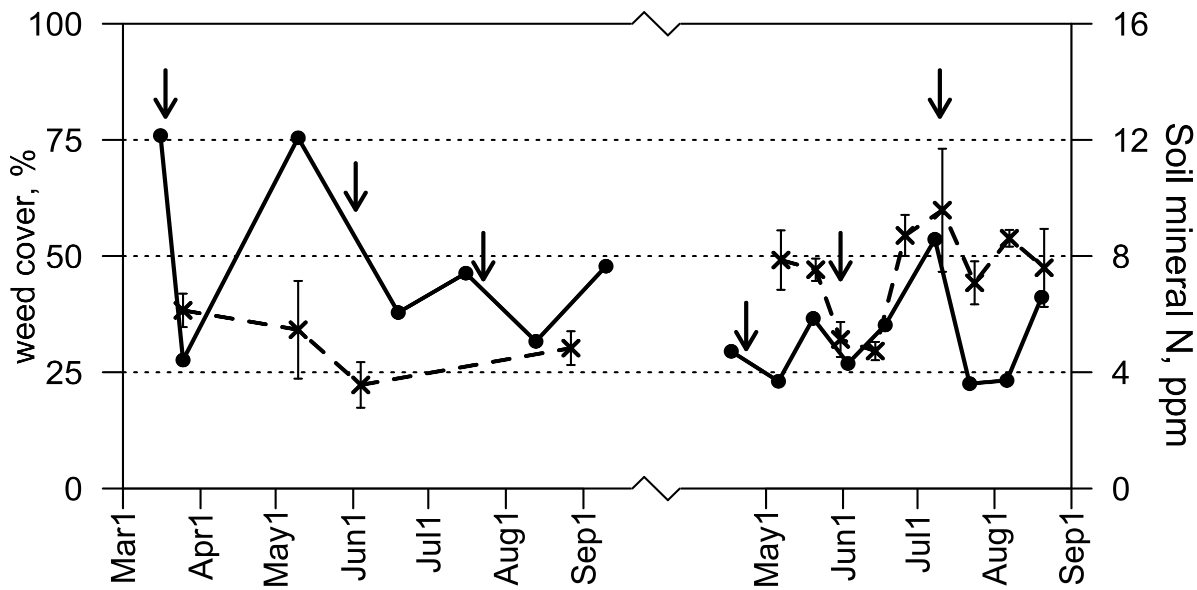


**Figure A6. Ground cover / soil N.** Weed cover (—●—) and soil mineral nitrogen ( —✕— ) over both sampling years at the orchard field site. Arrows indicate cultivation dates. Bars indicate standar error of the mean in the mineral N curves at 95% confidence.

**Natural enemy habitat**

In organic and low-spray orchards and vineyards, ground predators can provide some degree of native biocontrol for pests, minimizing damage from minor pests and dampening outbreaks of major ones. We wanted to assess whether the habitat on the orchard or vineyard floor would affect their population and activity. We set up traps to catch ground predator insects and assess the difference in predator populations between the two types of floor management.

There was not a consistent difference between herbicide and cultivation, except in the very dry conditions of 2012, when it appears that the shelter offered by slightly more weed cover provided a better habitat for them. Also, we caught roughly ten times as many ground predators in plots with a more diverse weed understory - with plantain, clover, ragweed, mixed grasses, alyssum, spotted knapweed, and others - compared to plots with only sod as ground cover.

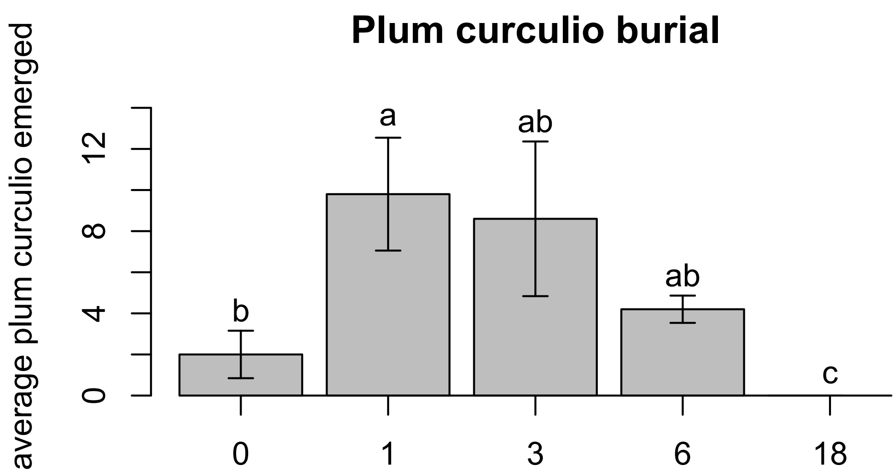


**Figure A7. Lab plum curculio burial results.** Number emerging (vertical) by depth of burial in inches (horizontal).

**Insect Pest Burial**

Most insect pests have some life stage that is on or in the soil. We investigated whether it's possible to disrupt the life cycle of two apple pests - the plum curculio and codling moth - by burial at critical life stages. For plum curculio in apples, they can be hit with a cultivator after June drop while the larvae are still in the fruit on the ground. Codling moth can be hit with a cultivator before first flight in the spring or after harvest in the fall, as long as you have minimal pupation sites in your trees and/or posts, which forces them to pupate in the leaf litter. We found that 70% of codling moth and 50% of plum curculio were buried by the spider cultivator. We also buried individual insects in the laboratory to find out the degree of mortality from burial. We found that *more* plum curculio were able to emerge as adults if they were buried under 1-6 inches of wet sand than if left on the surface (Figure A7, below). Codling moth, on the other hand, were unable to emerge from even 1/3 inch of damp sand, as long as they were buried *after* pupation (Figure A8a, next page). Some codling moth larvae that were buried were able to emerge, though very few of them made it to adulthood (Figure A8b, next page).

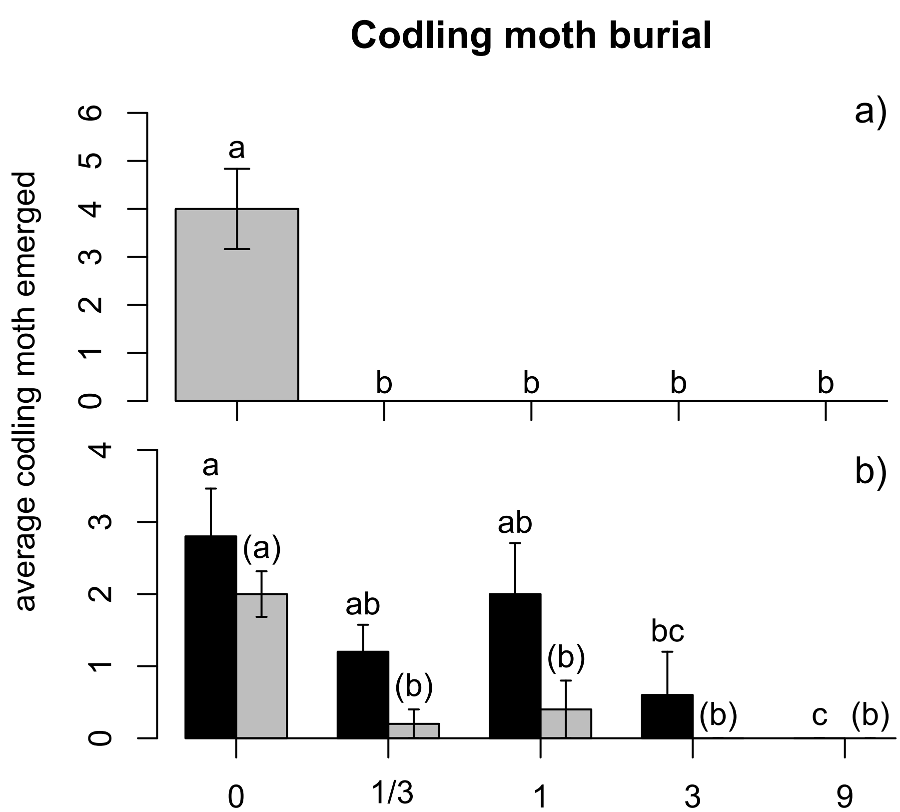


**Figure A8. Lab codling moth burial results.**
Number emerging (vertical) by depth of burial in inches (horizontal).
a) emergence from diapausing larvae buried in sand;
b) emergence from active larvae buried in potting soil; larvae in black, adults in grey.

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