Mulch Effects on Squash (Cucurbita pepo L.) and Pollinator (Peponapis pruinosa Say.) Performance

Thesis

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By

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Abstract
Growing interest in sustainable, local food production has created incentives for crop producers in urban areas to grow food for local consumption using low chemical inputs and sustainable or organic management techniques. Weeds represent a major obstacle to any organic crop production system and for small-scale producers in urban environments there is a need for organic weed control methods that are inexpensive, sustainable, and effective. Mulch has been successfully used for weed control in numerous fruit and vegetable crops. *Cucurbita pepo* has a high pollination demand and the native, ground-nesting bee, *Peponapis pruinosa*, provides the majority of the crop's pollination requirement. *Peponapis pruinosa* nests directly in crop fields and the nests can be disturbed by tillage operations used for weed control. Mulches that utilize municipal waste materials may provide a sustainable weed control strategy for application in urban *C. pepo* plantings that is more benign to *P. pruinosa* than tillage. Novel mulch materials remain to be investigated for their effects on weed suppression, crop performance, crop nectar and pollen production, and bee nesting. Field and greenhouse studies of pumpkin and zucchini were conducted in 2011 and 2012 to determine the effects of polyethylene black plastic, woodchips, shredded newspaper, a combination of shredded newspaper plus grass clippings (NP+grass), and bare soil on soil characteristics, *C. pepo* pollination, fruit production and overall crop performance, weed abundance, pest and disease pressure, and *P. pruinosa* nesting. Woodchip, newspaper and NP+grass mulches
conserved soil moisture, with newspaper mulch resulting in the highest and plastic in the lowest soil moisture levels overall. NP+grass mulch accumulated the most soil growing degree days over the course of a season and had a positive effect on pumpkin and zucchini plant growth, producing plants greater in size and with higher leaf chlorophyll content than plants grown on bare soil. All mulch treatments resulted in higher pumpkin yield than bare soil. Misshapen, unmarketable zucchinis occurred more frequently in black plastic than in the other mulch treatments. No measurable differences in floral resource production or crop pollination were found among mulch treatments, so misshapen fruits present in black plastic may have been due to high soil temperatures. During the critical period for weed control, four to six weeks after planting, suppression of weed biomass ranged from 74% by NP+grass to 100% control by black plastic in 2011, and from 99% in woodchips to 100% control by plastic, newspaper, and NP+grass mulch in 2012. NP+grass mulch may have been compromised in 2011 due to wet weather conditions leading to more rapid degradation of grass clippings and higher weed emergence. Bee nests were located within bare, newspaper, and NP+grass plots, so *P. pruinosa* nesting was not prevented by these mulches. Shredded newspaper and shredded newspaper combined with grass clippings should be considered for further research because of their potential to increase sustainability within urban agricultural systems by providing adequate weed suppression and improving crop performance of *C. pepo* with no apparent negative impacts on pollination or *P. pruinosa* nesting.
Dedicated to Ernie, Uzi, and Mama Earth
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CHAPTER 1

Literature Review

1.1 Introduction

Soil tillage is considered the most energy-consuming of all agricultural field operations (Chauhan et al. 2012). In addition to the cost of fossil fuels used to run machinery for tillage, the time and labor required for tillage are also significant costs to farmers. The advent of herbicides has greatly reduced the need for tillage (Gianesse and Reigner 2007), but has generated new and different problems. The use of herbicides on wide swaths of weeds in innumerable areas creates an enormous selection pressure on weed populations towards herbicide resistance. Resistance within five herbicide modes of action has already been well documented (Powles and Yu 2010). Aside from the ecological risks associated with herbicide use, there has been a recent interest in alternative weed control practices for organic growers who rely heavily on mechanical cultivation and/or timely hand-weeding in an effort to reduce costs and improve sustainability. Organic, as well as, conventional growers may value an alternative weed control strategy to tillage, since this practice causes soil erosion, the degradation of soil structure and microbial communities, and releases sequestered CO₂ back into the atmosphere (Hobbs et al. 2008; Gianesse and Reigner 2007). Due to concerns that the overuse of mechanical or chemical weed management methods may have negative impacts for human health and ecological integrity, plus added costs of time and labor for
growers, more sustainable weed control practices are needed to mitigate these effects while still maximizing yield (Liebman 2001). Sustainable practices are especially important in urban areas where increasing agricultural activity occurs in proximity to high-density human populations.

The use of mulch to suppress weed growth by providing a physical barrier may reduce the need for mechanical and chemical weed control in areas where environmental quality and soil conservation are of particular importance. Mulching has proved effective for weed control in fruit and vegetable crops with the added benefit that it limits potentially harmful chemical exposure to beneficial insects, such as pollinators. A wide variety of mulch materials has been studied, including but not limited to, plastic film, wood fiber, paper, and living or killed plant residues, but many novel mulch materials remain to be investigated with regard to their ability to suppress weeds and improve crop yields. It will also be important to investigate the effects of mulches on beneficial insects, such as crop pollinators, to ensure their overall positive effect on crop management.

For certain crops, such as squash and pumpkin (*Cucurbita pepo* L.), pollinators are essential for fruit set, therefore yield is tightly linked to adequate pollination (Klein et al. 2007). Although many species of bees pollinate *Cucurbita*, in much of the United States, a native specialist bee, *Peponapis pruinosa* Say., is the primary pollinator. Because its life cycle is tightly linked to its host plant, the bee nests in proximity to cultivated fields, often under the plants themselves. Any novel weed control method should be screened for its effects on the floral resources used by pollinators and for its impact on *P. pruinosa* nesting habitat. Mulches could influence crop growth and crop
floral resources for pollinators, such as the number of flowers and the amount of nectar or pollen per flower. They could also influence the availability of bee nesting substrate for ground-nesting species by altering soil surface characteristics, soil temperature and soil moisture. Finally, the presence of mulch could affect bee visitation to crops by influencing the cues (i.e., ground color, reflectivity) that guide bees to flowers. Many polyethylene plastic films contain UV-absorbing components to prolong the life of the material, which could influence the flight patterns of insect that use UV-reflectance patterns as cues for recognizing host plants (Costa et al. 2002). Bumble bees, *Bombus terrestris* L., differentiate between hosts while foraging using learned distinctions of color hue (Gumbert 2000). Mulch materials that result in greater differentiation of color hue between flowers and their background may increase visitation to those flowers by some insects.

1.2 Implications of urbanization and urban agriculture for pollinators

The current population of the United States is 311 million and is projected to grow at an increasingly rapid rate (U.S. Census Bureau, http://www.census.gov). Approximately 80 percent of our population lives in metropolitan areas and most agriculture is considered to be urban or urban-influenced because of its proximity to urban areas (Butler and Maronek 2002). The amount of urban land used for food production must increase because of population growth within urban areas and lack of non-urbanized land available for agricultural production (Lorenz and Lal 2009). Along with this increasing urbanization, the consumption of locally grown foods and organic foods has risen sharply in the United States over the past decade. In the past ten years the sale of organic food and beverages has risen from $1 billion to over $28.6 billion, with
the highest growth occurring in the sale of organic fruits and vegetables (Organic Trade Association 2011). A recent national survey indicated a consumer preference for local and organic produce over conventionally produced items. Fifty percent of consumers claimed they would choose locally grown produce, 28% would choose organic produce regardless of its origin, and only 9% would choose a conventionally produced product when given a choice of the three (Food Marketing Institute 2008). The growing interest in sustainable local food production has created incentives for crop producers, especially in urban areas, to grow food for local consumption using low amounts of chemical inputs and sustainable or organic techniques (McCullum et al. 2005).

Weeds are a major obstacle to any crop production system, but especially for organic producers (Walz 1999). Organic weed management strategies are especially appealing in urban environments because of the close proximity of crop production to people, which may preclude the use of chemicals for safety reasons, or the use of tillage because of a lack of space for large-scale, farm equipment. Organic weed control methods need to be sustainable, inexpensive, and accessible to be most useful for small-scale producers in urban environments. The use of municipal waste materials is mentioned within the United Nations Urban Agriculture Development Program’s definition of urban agriculture, which defines the industry as one “that produces, processes and markets food and fuel, largely in response to the daily demand of consumers within a town, city, or metropolis, on land and water dispersed throughout the urban and peri-urban area, applying intensive production methods, using and reusing natural resources and urban wastes, to yield a diversity of crops and livestock” (Smit et al. 1996).
There is ample information about pest insect populations in urban environments, however, there is less information available on beneficial insects within metropolitan areas. When thinking about how the urban environment may influence pollinator abundance and diversity, it is important to consider how human disturbances pose risks to insect populations. Significant disturbances within urban areas are isolation from natural habitat and habitat fragmentation. These anthropological disturbances affect different guilds of insects in different ways. For example, Williams et al. (2010) found that species which nest above ground were more negatively affected by isolation from natural habitat and agricultural intensification than ground-nesting species. This is presumably due to a lack of suitable nesting substrates for above-ground nesters. Ground-nesting bee species were more negatively affected by tillage than above-ground nesters and social bees were more negatively affected by isolation from natural habitat than solitary bees (Williams et al. 2010). Insect communities in urban areas can be diverse, although the number of insects may be low compared to a rural environment (Frankie and Ehler 1978; Cane 2005). Because many urban growers focus on fruit and vegetable crops, most of which require insect pollinators (Klein et al. 2007), low population numbers of insect pollinators may limit yield in urban environments. However, pollinators that are solitary, ground nesting bee species may be more abundant in urban environments than other bee species due to their resilience to anthropological, environmental disturbances such as habitat fragmentation and loss.

Spatial and temporal habitat heterogeneity can help support more diverse insect communities (Frankie and Ehler 1978; Tscharntke et al. 2012). Microhabitats that include different biotic and abiotic components can provide crucial resources for a diverse insect
community. For example, in a study conducted by Tylianakis et al. (2005), bee and wasp diversity was higher on a per plot basis (alpha diversity) in intensively managed agroecosystems, but diversity was greater on a landscape scale within agroecosystems with higher habitat heterogeneity (beta diversity). Cropping systems that incorporate multiple types of habitat in a mosaic support a more diverse insect community due to higher community dissimilarity (Tscharntke et al. 2012). Furthermore, this heterogeneity needs to exist at multiple spatial and temporal scales (Tscharntke et al. 2012). Urban environments tend to be more heterogeneous than many traditional agricultural landscapes, providing diverse microclimates that can support diverse insect communities, including pollinators. Urban community gardens and green roofs, a fairly recent trend of growing plants on rooftops, within urban settings have been found to be suitable habitat for some bees, which is promising for the success of urban production of insect-pollinated crops (Matteson and Langellotto 2009; Colla et al. 2009).

The most hostile environment for bees may be intensely managed agricultural fields, when considering disturbances such as lack of habitat complexity, isolation from natural habitat and chemical use (Kremen et al. 2002; Roulston and Goodell 2011). To increase yields, farmers are planting more of their land area with crops and getting rid of fallow flower strips and hedgerows. These minor landscape elements provide important resources and habitat for pollinators foraging within agricultural fields (Tscharntke et al. 2012). Many bees, such as honeybees, bumblebees, and other twig-nesting species nest in forest edges and then travel to where floral resources are abundant to forage (Roulston and Goodell 2011), so isolation from this type of habitat can limit populations within agricultural fields. The use of chemicals in agricultural fields also makes them
inhospitable to bees. Pesticides and some herbicides and fungicides are toxic to bees, and when used extensively, they pose a significant threat to bee populations (Roulston and Goodell 2011). Some chemicals approved for use in organic production are also toxic or can have sub-lethal effects on bees (Roulston and Goodell 2011).

In urban areas, as well as rural, the goal of farming is to optimize crop yield. An important component of optimizing crop performance is to control weeds that compete with the crop. For crops requiring insect pollination, crop performance can also be influenced by how well the crop is pollinated. If the selected weed control strategy impedes crop pollination, crop performance will be reduced. Several studies have shown negative impacts of certain weed control strategies on pollinator performance as will be discussed hereafter (Julier and Roulston 2009; Holzschuh et al. 2008).

1.3 The importance of wild, native pollinators to agroecosystems

To keep up with human population growth, production of insect-pollinated crops will have to be increased and it will be important to maintain wild bee populations for the pollination service required by these crops (Aizen et al. 2009; Roulston and Goodell 2011). In looking at data from 200 countries, Klein et al. (2007) determined that fruit, vegetable, and/or seed production of 87 of the 124 leading global food crops producing at least 4 million metric tons annually depend on animal pollination, largely insect pollination. This accounts for 35% of global food production (Klein et al. 2007).

Although the percentage of food produced by animal-pollinated crops is smaller than that produced by self or wind-pollinated species, Steffan-Dewenter et al. (2005) point out that our diet would suffer nutritionally and culturally if the amount of food produced by animal-pollinated crops is reduced. Humans gain the majority of their caloric intake from
grains produced by wind-pollinated grasses, but acquire essential macro and micro-
nutrients from animal-pollinated fruits and vegetables. *Curcurbita pepo* was included
along with 12 other species in the category of species to which pollination is ‘essential’,
meaning that pollination would be reduced by 90% or more without animal pollination
(*C. pepo* fruit set would decline by 100% without pollinators) (Klein et al. 2007).

The decline in numbers of managed honeybee, *Apis mellifera*, colonies in certain
regions of the world, evidenced by decreased numbers of hives in the U.S. (National
Research Council 2007), highlights the risk of relying solely upon these bees for the
pollination of crops. Domesticated European honeybee colonies are commonly used to
provide the service of pollination for those crops that require insect pollination. However,
*A. mellifera* continues to be plagued by diseases carried by the mites *Acaris woodi* and
*Varroa jacobsoni* (Downey & Winston 2001; Chen et al. 2004), parasitic pests such as
the small hive beetle *Aethina tumida*, (Evans et al. 2003) and the microbial parasite
*Nosema ceranae* (Higes et al. 2006). In addition, bee keeping is challenged by
Africanization, crossing and genetic integration of the domesticated honeybee with the
highly aggressive African strain in some tropical and subtropical regions of the North and
South America, causing the managed bees to become more defensive and thus more
difficult to manage (Canto-Aguilar & Parra-Tabla 2000). Improper use of pesticides and
herbicides can lead to the contamination of pollen and nectar resources causing them to
be toxic to bees (Ingram et al. 1996).

Despite the problems managed honeybees face, data compiled by Aizen and
Harder (2009) indicate that the global population of managed honeybees has increased by
approximately 45% over the last half century. They argue that the challenge we may
actually be facing is insufficient pollination of certain crops because the production of those crops is increasing more rapidly than managed honeybee populations can support. In the last fifty years the fraction of agriculture requiring insect pollination has risen by over 300 percent (Aizen and Harder 2009). Native, wild pollinators will help to provide insect pollination required by an increasing proportion of crops, since the service provided by the current global population of honeybees may not be adequate.

In addition to being increasingly difficult to manage and too few in abundance to provide pollination for the growing proportion of crops requiring insect pollination, *A. mellifera* is not always the most efficient pollinator for many crops. Canto-Aguilar and Parra-Tabla (2000) discovered in a direct comparison study that *Peponapis limitaris*, a wild, native pollinator to the U.S., was a far more efficient pollinator for *Cucurbita moschata*, a type of squash, than *A. mellifera*, removing and depositing approximately four times the amount of pollen and making significantly more floral visits. The authors suggest that this high floral visit frequency is due to a strong relationship between the native pollinator and the crop, its natural host plant, which allows the native pollinator to better service the flowers (Canto-Aguilar and Parra-Tabla 2000). *A. mellifera* can even compete with native pollinators for floral resources, causing undue pollination inefficiency due to a reduction in the health and survival of native species that may be more specialized (Canto-Aguilar and Parra-Tabla 2000).

Many examples of higher pollination efficacy with wild pollinators compared to honeybees have been demonstrated. In a study conducted with sweet cherry (*Prunus avium* L.) higher pollination was achieved due to the presence wild pollinators associated with greater areas of high diversity pollinator habitat within the surrounding landscape.
(Holzschuh et al. 2012). Wild bees were found to be the primary pollinators of tomato (Solanum lycopersicum L.), bell pepper (Capsicum annuum L.), muskmelon (Cucumis melo L.), and watermelon (Citrullus lanatus (Thunb.) Matsum. & Nakai), in both organic and conventional fields (Winfree et al. 2008). The pollinator assemblages visiting watermelon were different than those visiting tomato suggesting that wild pollinator assemblages differ depending on the crop grown. Wild Bombus species exhibited higher pollen deposition onto stigmas of apple blossoms (Malus domestica Borkh.) in comparison to honey bees further indicating the potential for more efficient pollination by wild bee species (Thomson and Goodell 2001).

In addition to the pollination services provided by wild pollinators themselves, the presence of wild species has been shown to increase the pollination efficiency of honeybees. Greenleaf and Kremen (2006) found a five-fold increase in honeybee pollination efficiency on sunflower (Helianthus annuus L.) when honeybees experienced behavioral interactions with wild pollinators. When honeybees encountered a wild bee they moved more frequently between male and female flowers increasing pollination and seed set. This frequent movement between flowers did not occur when honeybees encountered other honeybees (Greenleaf and Kremen 2006).

The foraging habits of native bees versus honeybees have been reported to be substantially different in the case of an insect-pollinated shrub, Dillwynia sieberi Steud., from Australia (Lomov et al. 2010). Honeybees spent up to 10 min foraging at the same plant, and in the processes increased self-pollination, whereas, native pollinators foraged for only a tenth as long before moving to another plant, effecting a higher rate of out-crossing. Similar differences in foraging patterns could affect crop pollination and yield.
Differences in foraging behavior could reflect differences in the life history strategies of the bees (Lomov et al. 2012; Greenleaf and Kremen 2006). Honeybees are social insects that live together in perennial colonies and share foraging and other duties. No native bees to the US exhibit this level of sociality. Most native wild bees, with the exception of *Bombus* species, have a solitary life history, which means that individual females forage and nest independently. They must locate all necessary resources within a limited flight range from their nest. Thus, whether they are present to forage and pollinate crop plants or not can depend on the suitability of the habitat for nesting near the crop plant.

Although it is clear that native bees may be superior to honeybees for the pollination of certain crops, little is known about wild, native pollinator species and their activity within an agricultural setting. Only 24 out of 57 insect-pollinated crops produced around the globe have been investigated to see what wild pollinator species visit and determine their contribution to crop pollination (Klein et al. 2007). Since less than half of insect-pollinated crops have been studied to determine wild pollinator contributions to crop pollination, more research on wild pollinator species is needed.

1.4 Risks to pollinators

1.4.1 Habitat loss and isolation from natural areas

Rapid population growth demanding a greater food supply will lead to a greater amount of land used for food production reducing the amount of natural and semi-natural areas suitable for pollinator habitat in the future. These areas provide nesting and floral resources for a diversity of insect pollinators (Steffan-Dewenter et al. 2002; Kremen & Chaplin 2006; Steffan-Dewenter et al. 2006). Multiple studies have shown reduced pollination services with increasing agricultural intensification and a positive correlation
between the percent of natural habitat surrounding a crop field and the pollination services delivered (Klein et al. 2007; Blanche and Cunningham 2005; Morandin and Winston 2005, 2006; Kremen et al. 2002, 2004; Chacoff and Aizen 2006; Ricketts 2004; De Marco and Coelho 2004; Greenleaf and Kremen 2006; Heard and Exley 1994). Although providing habitat for pollinators is crucial, Cane et al. (2006) argues that in order to provide the resources needed by specific pollinators we must do more than simply provide natural areas as habitat. Knowledge of the specific pollinator’s life history traits is required to provide habitat that is suitable (Cane et al. 2006; Williams et al. 2010).

The use of landscape management practices that increase native pollinator density by increasing the habitat’s carrying capacity, would benefit agricultural production on a local scale (Klein et al. 2007). For example, modifying cultivation practices or retaining adjacent natural areas around cultivated fields to increase safe nesting habitat could improve bee densities on crops (Shuler et al. 2005). Also, carrying capacity could be increased by reducing the risk of pollinator population crashes; by ending the use of broad-spectrum insecticides during bloom periods, especially those that have been found to contaminate pollen and nectar (Kevan 1975; Wood 1979; Delaplane & Mayer 2000). Nesting requirements, floral hosts, and foraging periods when pollinators are susceptible to pesticide spray differ according to species, so knowledge of specific species characteristics is crucial (Cane et al. 2006).

Gemmill-Herren and Ochieng (2008) found that arable weeds provided most of the alternative forage resources for wild pollinators of eggplant (Solanum melongena). Altering the community of weedy species in and around crop fields may influence wild
pollinator densities present in crop fields due to a spill-over effect from surrounding habitat (Tscharntke et al. 2012). While examining whether organic cropping systems fostered higher bee abundance in adjacent non-crop areas at both a landscape and local scale Holzschuh et al. (2008) found that pollinator abundance and diversity were higher in fallow strips adjacent to organic fields than in fallow strips adjacent to conventional fields. The authors posited that increased flower cover and species richness of flowering plants provided more floral resources for pollinators in organic fields compared to conventional fields (Holzschuh et al. 2008). This suggests that the use of herbicides decreases the abundance and diversity of insect-pollinated weed species compared to organic weed control methods (Holzschuh et al. 2008). These plants provide additional foraging resources for the bees that nest and over-winter in the adjacent fallow areas. It also illustrates how the survival of pollinators in an environment depends on more than just the absence of insecticide. Heterogeneity within the landscape of an agroecosystem is essential for providing diverse habitats to increase wild pollinator species richness and abundance.

1.4.2 Floral resources

On a more local scale, the quality and quantity of suitable floral and nesting resources available determines the survival and abundance of particular species along with the exposure to incidental risks. According to Roulston and Goodell (2011) bee species abundances should increase when food and nesting resources increase, and should decrease in response to increases in risk factors such as tillage, parasites/disease, predators, and pesticides. Since the primary energy source for almost all bee species is floral nectar and pollen during both the larval and adult life stages (Michener 2000) it is
arguably the most potentially limiting resource. The breadth of diet and foraging range of a particular bee species impact the amount of local food resources that are needed to support the species (Roulston and Goodell 2011).

Even when floral resources are abundant locally, the proximity of bees to resources, i.e. where nest sites are in relation to floral resources, can affect foraging and pollination productivity (Roulston and Goodell 2011). However, the amount of natural habitat or its proximity to a crop field should not necessarily be used as a predictor for bee abundance, because not all natural areas provide abundant floral resources. Bees are mobile and can aggregate around pulses of rich resources. Temperate deciduous forests, the predominant vegetation type in the Eastern United States, often fail to provide many floral resources during the summer months when most crop pollination is needed (Heinrich 1976; Winfree et al. 2007). Therefore, some bees, A. mellifera for instance, can be expected to travel great distances from habitat where they nest to forage from areas rich in floral resources, such as an agricultural field in bloom. However, for certain solitary bee species, proximity of floral resources to their nest sites is more important since they may not to travel as far.

1.4.3 Nesting resources

Although floral resources may be the most limiting resource for pollinators, nesting resources can limit bee populations as well (Roulston and Goodell 2011). The nesting habitats of bees are quite diverse including above ground nesting species that utilize wood as a nesting substrate and species that nest below ground in soil. The substrates available for nesting are essential to the survival of bee populations, which may be why above-ground nesting species are more affected by overall agricultural
intensification than ground-nesters due to the lack of trees in intensely farmed areas (Williams et al. 2010). Soil at field margins and in fields themselves is available for ground-nesting species in agriculturally dominated landscapes. However, weed management strategies such as tillage may affect the availability of soil for bee nesting.

The purpose of bee nests is to protect adults and developing larvae from predators and parasites, extreme environmental conditions, and other incidental harm. Most ground-nesting bee species excavate simple nesting cavities in the form of tunnels in the soil (Roulston and Goodell 2011). Local nesting density of ground nesting bees has been correlated with various environmental conditions including soil moisture, ground cover, slope aspect, and soil compaction (Williams and Kremen 2006; Potts et al. 2005). A study by Julier and Roulston (2009) indicated a strong preference for nesting by *Peponapis pruinosa* on irrigated soils, and Potts et al. (2005) found a nesting preference for bare ground opened by fire disturbance. Different species have different nesting habitat, thus the more heterogeneity there is in soil characteristics, the more bee species that can be expected to be present. However, it is difficult to isolate the effects of nest site availability from that of floral resources and therefore we lack a clear understanding of the scale and severity to which nest site limitation occurs (Roulston and Goodell 2011).

In addition to nest site limitation, the destruction of nests located in the soil of agricultural fields poses a threat to wild, ground-nesting species within agroecosystems. Many ground nesting bee species place their brood cells within 30 cm of the soil surface (Mathewson 1968). Tillage depths commonly reach from 15-30 cm, therefore some or all of these subterranean bee nests may be destroyed with tillage. The primary purpose of tillage is weed management, yet alternatives exist. Some of these alternative weed
management strategies should be investigated for their impacts on ground-nesting pollinator species.

1.5 Mulch: an alternative weed management strategy

Mulches offer a weed management strategy that is suitable for small-scale, organic production and is also practical for use in urban environments. Mulches reduce the need for tillage and herbicide application by preventing the germination of weed seeds and the emergence of weed seedlings that do germinate. Mulches function as a physical barrier to weed emergence and alter the soil microclimate to impede weed seed germination.

1.4.1 Mechanisms of weed suppression by mulches

Mulches alter the soil microclimate by regulating temperature, moisture, and light conditions for weed seeds beneath the mulch material. Altering the microclimate that a weed seed encounters can adversely affect seed germination, thereby suppressing weed growth. Mulch materials can also inhibit weed growth by providing a physical barrier to emergence and impeding the light necessary for growth.

There are many environmental conditions that can trigger the germination of weed seeds in the soil seed bank. For example, high temperatures tend to break the dormancy and induce germination of winter annuals, which germinate in late summer and overwinter as a rosette before blooming in the spring (Baskin and Baskin 1998). In contrast, a period of low temperatures breaks the dormancy of many summer annual species (Baskin and Baskin 1998). Using a mulch material that reduces temperature fluctuations and extremes may impede dormancy break and germination of those seeds that require high temperatures, low temperatures, or large fluctuations in temperature.
Light is another environmental factor influencing germination that is altered by the application of mulch. The depth at which seeds are buried in the soil has the greatest effect on how much light they are exposed to, but mulch further reduces light penetration of the soil. Although mulches dramatically reduce seed exposure to light, some seeds can enter a secondary dormancy when kept in prolonged periods of darkness and therefore remain part of the seed bank (Baskin and Baskin 1998). Mulches can also increase soil water retention, which can influence seed germination. For some seeds, excess moisture can inhibit germination by creating a barrier for oxygen exchange that limits aerobic respiration in the cells of seeds (Baskin and Baskin 1998). Furthermore, mulches can decrease the level of water fluctuation in the soil. Wet and dry cycles are necessary for some weed seeds to break dormancy (Baskin and Baskin 1998).

Aside from their impact on weed seed germination, mulches also influence a seedling's ability to emerge through the soil and compete with crops for space, light, water, and nutrients. Teasdale and Mohler (2000) demonstrated that the success of a weed emerging through a mulch material depends upon the seedling's ability to grow around the obstructing mulch material under limiting light conditions. Therefore, structure of the mulch material, which determines the presence or absence of gaps allowing light and seedling penetration, will determine how well the mulch slows weed emergence. Teasdale and Mohler (2000) determined that mulch materials which had the great proportion of their volume occupied with mulch elements produced the highest light extinction coefficients, thus they allowed less light to penetrate down to the soil surface. Light deprivation tends to lower weed seedling emergence, but not for all weed species (Teasdale and Mohler 2000), nevertheless weed emergence decreases exponentially as
the mass of the mulch applied increases (Teasdale and Mohler 2000). The suppressive ability of a mulch material also can be influenced by the presence of allelopathic chemicals, which are released by one plant to deter the growth of another (Rice 1974), or by effects on the soil microclimate.

1.4.2 Polyethelene, black plastic mulch

Polyethylene or polyvinyl plastic film has been successfully used for weed suppression and for earlier season harvests since the 1960s (Gruda 2008). Plastic mulch is often used in vegetable and fruit production for weed control in both organic and conventional farm operations and is combined with herbicide and pesticide use on conventional farms. There are many advantages as well as drawbacks to using plastic mulch for weed control. Black, polyethylene plastic is an impervious material with no gaps and often is 100% effective in suppressing weeds (Cirujeda et al. 2012). This impervious property of black plastic mulch also makes the material impervious to water, which can conserve water if drip irrigation is used beneath the material. However, it also prevents water infiltration from above and results in increased water runoff. Rice et al. (2001) found that the use of black plastic in tomato resulted in 2-4 times more water runoff and at least 3 times more sediment runoff than in plots where hairy vetch was used as mulch (see Table 1). Black plastic used in combination with chemical application could lead to off-site movement of herbicides and pesticides that can have negative environmental and human health implications (Rice et al. 2001).

Another disadvantage of plastic film mulch is its tendency to heat the soil below, causing overheating of the rhizosphere in warmer climates or during the heat of the summer, which can be detrimental to growth due to root cell death or decreased microbial
populations (Gruda 2008). Furthermore, using plastic film as mulch requires specialized equipment for application and added time for removal of the material since it does not degrade in the field (Díaz-Pérez and Batal 2002). Finally, the disposal of polyethylene film has enormous ecological costs. As of 1995, around 100,000 metric tons of agricultural plastic are either landfilled or burned each year (Anderson et al. 1995) and most likely this figure has increased in recent years. In addition to the removal and disposal costs of plastic mulch, polyethylene is a petroleum-based product that also consumes fossil fuels in the process of being synthesized (Anderson et al. 1995).

1.4.3. Biodegradable, cellulosic mulches

Degradable plastic mulches offer an attractive alternative to black plastic. One such product tested by Cirujeda et al. (2012), controlled weeds as effectively as black plastic. However, degradable plastic may need several seasons to degrade completely (Anderson et al. 1995) and is often very costly (Cirujeda et al. 2012). Paper mulch can provide as effective weed suppression and soil water conservation as plastic mulch, plus it is biodegradable and has no disposal costs (Anderson et al. 1995; Harrington and Bedford 2004; Cirujeda et al. 2012). Paper mulch may offer better weed control than plastic mulch in some cases. For example, it controlled a problematic weed species, *Cyperus rotundus*, which had failed to be controlled with plastic mulch (Cirujeda et al. 2012). Similar yields to black plastic have also been achieved with paper mulch when compared to plastic in lettuce, tomato, and summer squash (Toth et al. 2008; Cirujeda et al. 2012; Anderson et al. 1995; Coolong 2010). Paper mulch can take many different forms and the performance of paper mulch will vary according to the type of paper used
and how it is applied, field management practices, and environmental conditions (Coolong 2010).

Not only does the type of paper influence the efficacy of the mulch material for weed control, but paper type can have environmental and economical impacts as well. The paper’s origin and the amount of carbon released in its production should be taken into account. Using recycled paper has the advantages of providing a new market for a waste material, conserving resources, and sparing landfill space (Anderson et al. 1995). Recycled newsprint is a resource available in great quantities especially in and around urban centers (Paper Industry Association Council 2007). In the past, there has been concern about the carbon-based ink, which contains polycyclic aromatic hydrocarbons (PAHs), used for printing on newspaper. PAHs are known human carcinogenic compounds that when applied to land can build up in soil be unsafe (Anderson et al. 1995). However, in recent years, most, if not all, newsprint has switched to soy-based ink (Anderson et al. 1995). Applying newsprint to land no longer poses a threat to human health or environmental quality and is acceptable under organic certification as long as there are no ‘glossy’ paper contaminants (USDA 2008). In most areas of the country newsprint can be obtained for free, but it can also be obtained from companies that use it as livestock bedding for approximately $10-75 per ton (House and LaMuth). One could obtain either loose printed newsprint or rolls of unprinted newsprint, which are a waste material from the newspaper printing process. In some applications, rolls of paper are applied as mulch in a similar manner to sheets of plastic mulch (Shogren 2000; Cirujeda et al. 2012).
Most existing information about paper mulch focuses on sheets of paper laid flat atop the soil surface, but some information exists on using shreds of newspaper as well. There are two main disadvantages to using sheets of paper mulch: (1) when applied with a mechanical layer, paper is not as flexible as plastic and is subject to ripping and tearing, and (2) when the edges of sheets of paper are buried, they degrade rapidly lessening the paper’s efficacy at controlling weeds (Grossman 1991). Rolls of paper mulch are also much heavier than plastic and, because paper is susceptible to tearing, its application is slower (Harrington and Bedford 2004). Shogren (2000) found that untreated paper applied to the soil surface disintegrates in roughly 8 weeks, whereas coating papers with oils and resins delayed degradation to 12 weeks (Shogren 2000) but others have found that coating paper had no significant effect to retard degradation (Anderson et al. 1995). One way to ameliorate these issues may be to use shredded paper rather than rolling it out in sheets.

Applying paper to the soil surface as a particulate mulch without burying any of the paper seems to greatly reduce the paper’s weathering and decomposition compared to paper applied as a sheet with the sides buried similar to how plastic mulch is applied. Weed populations were higher in plots mulched with sheets of newspaper than in plots mulched with shredded newspaper due to more rapid degradation of the sheet newspaper (Sanchez et al. 2008). Pellett and Heleba (1995) observed that wetting the shredded newspaper and compressing it with a lawn roller after application kept the material from blowing away in the wind. Researchers have also used pellets and crumbles of paper to ameliorate the problem of shredded paper blowing away in the wind (Edwards 1997).
Shredded newspaper has been tested with many different crops and has shown promise as an effective mulch material. In a study where shredded newspaper was applied at a thickness of 10 and 15 cm, weed germination was suppressed for two seasons without any negative effect on two of the three nursery crops studied (Pellett and Heleba 1995). Comparable weed suppression to black plastic has been demonstrated with the use of shredded newspaper mulch in tomato, and increased yields in corn and soybeans were achieved using shredded paper compared to straw mulch (Grassbaugh et al. 2004; Munn 1992; Table 1.1). Yields of cucumber were unaffected by mulching with shredded newspaper when used in high tunnels (Sanchez et al. 2008).

Non-composted recycled paper products have a high carbon to nitrogen (C:N) ratio of approximately 500:1 (Edwards 1997). When materials high in carbon are added to soil, microorganisms that feed on carbon-containing materials thrive deplete the soil of plant-available nitrogen by converting inorganic N to organic N, which is generally unavailable for plant uptake. Nitrogen depletion from adding high C:N materials to the soil is a drawback with the use and incorporation of any type of carbon-based mulch material into the soil, but is extremely pronounced with the use of paper. For instance, leaf material, which is also very high in carbon, has a C:N ratio of only 50:1 (Wyenandt et al. 2008). However, there may be ways of ameliorating this problem by combining paper with materials high in nitrogen to achieve a more balanced C:N ratio.

1.4.4 Plant residue mulches

Mulches made from plant residues also provide an alternative to using plastic mulch. They tend to be less effective at controlling weeds than plastic since they often contain gaps between leaves and stems of the plant residue. However, there are other
benefits achieved from using plant residues that improve crop performance and provide ecological benefits such as reducing the risk of soil erosion, increasing water conservation around crop plants, and adding soil organic matter (Mulumba and Lal 2008). Application of plant residues to the soil surface lessens rain drop impact which can greatly reduce surface runoff (Findeling et al. 2003; Rees et al. 2002). Soil water retention is increased when surface residue serves as a vapor barrier to moisture loss, which further decreases water runoff and increases water infiltration (Mulumba and Lal 2008). Soil water conservation benefits crop plants by providing the plants with more water and also reducing the amount of nutrients lost through leaching and runoff (Rees et al. 1999). Increasing soil organic carbon through vegetative mulching also has positive effects on soil structure and quality including increased formation of soil aggregates, water infiltration, and resistance to erosion and compaction (Saroa and Lal 2003).

Many types of plant residues exist that are suitable for use as mulch materials. Corn stubble, wheat and barley straw, wood fiber chipped from downed trees, municipal leaf waste, and even sheep’s wool, an animal residue, have all been used as mulching materials (Duppong et al. 2004). Wood fiber is a commonly used mulch material, however, it tends to be relatively expensive (but can sometimes be obtained for free from municipalities). An advantage of wood fiber mulch is that is can be incorporated directly into soil without any additional removal or disposal costs (Gruda 2008), unlike plastic mulch. Wood fiber mulch can also be applied and distributed by hand around crop plants without any specialized equipment (Gruda 2008). Gruda (2008) reported that wood fiber mulch does not allow light penetration, but remains permeable to water and air (see Table 1.1). Their study found no nutrient deficiencies due to incorporation of the mulch and
found increases in soil quality (Gruda 2008). Yields of common bush beans (*Phaseolus vulgaris*) and lettuce (*Lactuca sativa*), and head firmness of lettuce were increased with wood fiber mulch relative to bare soil (Gruda 2008).

Leaf mulch was found to improve pumpkin fruit size and increase the number of clean fruits produced compared to bare soil with herbicide application (Wyenandt et al. 2008). Using leaf mulch also provided more suitable conditions for customers to walk through fields in inclement autumn weather at a pick-your-own pumpkin patch (Wyenandt et al. 2008). Some plant residues have the potential to cause nitrogen immobilization because of a high C:N ratio. The high C:N ratio of leaf material could mean that the grower would need to supply additional nitrogen to crop plants. Wyenandt et al. (2008) found that, initially, plants suffered from N deficiency exhibited by lower chlorophyll content in leaves and leaf yellowing. However, after standard N fertilizer application (side-dressing), the plants recovered and no further deficiency was detected (Wyenandt et al. 2008). The C:N ratio of a mulch should be a major consideration when selecting a mulch material and steps may need to be taken to prevent or overcome N immobilization.

1.4.5 Mulch effects on soil microclimate and possible impacts for ground nesting bees

The most obvious difference between plastic film mulch and vegetative or shredded paper mulch is that plastic film is comprised of a solid sheet, whereas the others are made up of separate particles. Particulate mulches must be applied as thick layers to be effective for weed control. Even though they form a thicker boundary layer over the soil surface, they still contain spaces where organisms can travel through. In this way, plant residues or shredded paper mulch may allow squash bees to nest in and around crop
plants. Plastic film creates an impenetrable barrier to both weeds and insects that would not allow bee nesting accept where there is an opening in the plastic to allow the crop plant through. Jordan (2004) found that where woodchip mulch was present, there was actually an increase in insect abundance (see Table 1.1). Fewer pest insects have been reported with the use of polyethylene plastic (Szendrei 2010; Summers 2010; Table 1.1).

Black, polyethylene plastic has the ability to warm soil temperatures rapidly, which can benefit farmers by enabling early harvests of their crop (Anderson et al. 1995). However, this soil warming effect could have negative implications as well. When soil temperatures fall outside the optimum range for root growth, the conditions can be detrimental for plant growth and development (Teasdale and Abdul-Baki 1995).

Newspaper mulch tends to have an opposite, cooling effect on soil temperature as noted by Grassbaugh et al. (2004; see Table 1.1). A cooling effect on soil temperature may actually have a negative impact on squash and pumpkin since C. pepo is a warm season crop.

The type of mulch used may also influence floral resources that are available to pollinators. Nectar quantity and composition varies widely due to environmental factors such as temperature, soil moisture, and humidity (Fahn 1979; Cruden et al. 1983; Wyatt et al. 1992). Those mulches that decrease water infiltration may cause a decrease in the amount of nectar produced. Mulches that conserve water around the crop plants would likely have the opposite effect. Mulches that immobilize nitrogen may have an influence on the quality of the floral resources produced. Less available nitrogen may have an effect on the protein content of pollen or the sugar content of nectar due to the limited resources available for allocation towards reproductive tissues. The quality and quantity
of squash pollen and nectar, which provide the entire diet for *Peponapis pruinosa*, are critically important for bee survival. Although nectar rewards ensure the adequate pollination necessary for marketable fruit and vegetable crops, no research has been conducted to investigate the effects of mulches on floral resources.

### 1.5 Biology of *Peponapis pruinosa* and its host plant *Cucurbita pepo*

Over the past decade there has been an increase in the demand for pumpkin and squash crops resulting from the new-found popularity of agritourism in the U.S. which includes fall festivals, farm tours, and u-pick crops (Wyenandt 2008). There is a need for more research on weed control within pumpkin and squash crops that is safe for farmers, customers, and the bees that pollinate the crop. Many farmers are unaware of the presence of squash bee populations in their fields and the pollination service that they provide (Schuler et al. 2005). Increasing grower awareness of the presence and impact of squash bees for *C. pepo* pollination should also be a goal.

#### 1.5.1 Lifestyle characteristics

The study of oligolectic, or specialist, bee species is thought to be relatively simple because the resources available to the bees are easy to calculate and the foraging bees are easy to locate on their host plant (Roulston and Goodell 2011). Farms with consistent management practices also provide a good study environment since current generations of bees have developed from the resources that were available to the previous generation (Roulston and Goodell 2011). It is for these reasons that the squash bee, *Peponapis pruinosa*, and its host plant, *Cucurbita pepo* are good candidates for study.

*Cucurbita pepo* has a particularly high pollination demand for good fruit set to occur. Each flower is open for one day, opening between 6 and 7 am and closing at
approximately noon (Tepedino 1981; Nepi, Pacini and Willemse 1996). Also, for optimum seed set and fruit diameter, female pumpkin flowers must be visited from seven to over twelve times depending on the variety and the bee species that visits (Walters and Taylor 2006; Julier and Roulston 2009). The native pollinator *Peponapis pruinosa* pollinates pumpkins efficiently, having evolved closely with plants in the genus *Cucurbita*. *Peponapis pruinosa* is most active early in the morning while pumpkin flowers are still open. Although many farmers bring in European honeybee hives for pollination of their squash and pumpkin fields, *P. pruinosa* can preempt other bees at the flowers, often collecting most of the pollen and performing most of the pollination before honeybees begin to work the flowers (Williams et al. 2009; Tepedino 1981; Cane et al. 2011).

*Peponapis pruinosa*, or the squash bee, is native to North America having extended its range northward from Mexico and now occupies most of the continental United States and eastern Canada with the domestication and spread of continuous *C. pepo* plantings (Hurd et al. 1971; Kevan et al. 1988). *P. pruinosa* is a widespread pollinator, even in regions where there are no wild *Cucurbita* species present, making cultivated *Curcurbita* species its sole foraging resource (Schuler et al. 2005). Maintaining independent refuge populations of *P. pruinosa* far from agriculture is not possible in regions of the USA that lack wild populations of *Cucurbita foetidissima*, the native host of squash bees (Schuler et al. 2005).

*Peponapis pruinosa* is a solitary, ground-nesting bee that produces one generation per season (Williams et al. 2009). The females make one to several nest hole(s) in the soil throughout the season, where they deposit their eggs and provision solely with *Cucurbita*
pollen (Figure 1.1). In June of the following year in Ohio the next generation of bees emerges from the previous year’s nest sites (Williams et al. 2009). Female squash bees visit male flowers in search of nectar and pollen to provision their nests and female flowers for nectar to feed on. Male squash bees visit male and female flowers to feed on nectar and to mate with females. Males also sleep in the closed flowers (Schuler et al. 2005), while females return to their below-ground nest once squash blossoms close at midday. Female *P. pruinosa* prefer to nest directly under the squash and pumpkin plants from which they are foraging (Julier and Roulston 2009). They may also prefer to nest in irrigated soils with low clay content (Roulston and Goodell 2011).

*Peponapis pruinosa* would be expected to be especially sensitive to tillage since it has no non-crop host plants in most of its range, it prefers to nest directly in crop fields, and it places its brood cells within tillage depths. However, studies on the effects of tillage on *P. pruinosa* give conflicting results: Shuler et al. (2005) found that *P. pruinosa* populations were reduced in tilled fields and Julier and Roulston (2009) found no difference in *P. pruinosa* flower visitation between tilled and non-tilled fields.

There are two possible mechanisms for how this bee could survive tillage: 1) by nesting below or outside the tillage zone, deep in the field or in field margins, or 2) strong philopatry, which is the behavior of returning to nest in one’s own birthplace. In the first scenario, we would imagine that a significant proportion of nests within the tillage zone would still be destroyed. If philopatry occurs, which many ground-dwelling bee species demonstrate, this could lead to the development of “safe sites” (Yanega 1990). In this second scenario, an initial bottleneck would occur with an increasing abundance of nests being located at safe sites over time as long as they remain safe. Regardless of whether
some ground-nesting are able to survive agricultural tillage, it remains apparent that
tillage is a considerable risk for these insects.

1.5.2 Nectary biology of *Curcurbita pepo*

It is important to know about the physiology and biology of squash flowers to
better understand how they are pollinated and what can limit pollination. *Curcurbita pepo*
is a monoecious plant having separate male and female flowers that require insect
pollination. The morphology of male and female flowers differs. The male flower has
three fused filaments that form a column supporting five fused anthers. The nectary of the
male flower is a cavity located within the base of the filament column that is accessible
through three nectary pores (Nepi, Pacini and Willemse 1996). The female flower has an
inferior ovary that when pollinated becomes the harvested fruit, called a pepo. The ovary
contains hundreds to thousands of ovules, most of which will form seeds if the
developing fruit is not aborted by the plant (Cane et al. 2011). Three partially fused styles
form a column that supports the bipartite lobes of the stigma in the female flower at the
base of which sits the circular channel that is the flower’s nectary (Nepi, Pacini and
Willemse 1996). Nectar secretion coincides with anthesis of both the male and female
flowers (Nepi, Ciampolini and Pacini 1996).

*Curcurbita pepo* is considered a ‘super-producer’ of floral rewards meaning that it
is extremely rewarding compared to most bee-pollinated flowers (Nepi, Guarieri and
Pacini 2001). Both male and female flowers provide nectar, although the female flowers
provide larger quantities of nectar that has a higher in sugar content compared to male
flowers (Nepi, Pacini and Willemse 1996, Nepi, Guarieri and Pacini 2001). In a study
conducted by Nepi, Guarieri, and Pacini (2001) the amount of nectar produced by squash
blossoms averaged approximately 43 µl/hour but totaled as much as 118 µl over one day for female flowers. Male flowers had a much lower secretion rate of approximately 28 µl/hour (Nepi, Guarieri and Pacini 2001). Male flowers produce about 40,000 relatively large pollen grains (136 µm in diameter) or 580 mm³ of pollen per flower (Lau and Stephenson 1993). The sugar content of nectar from female flowers is significantly higher than in males, 440 mg/mL versus 325 mg/mL (Nepi, Guarieri and Pacini 2001). *Cucurbita pepo* also has the ability to reabsorb unused nectar to conserve its resources and make use of the materials later (Nepi, Guarieri and Pacini 2001).

In comparing the floral rewards of squash and pumpkin to those of other insect-pollinated plants, *C. pepo* provides more pollen and nectar per flower than any other bee-dependent crop (Cane et al. 2011). Consider blueberry, *Vaccinium ashei* Reade, another insect-pollinated crop hosting a bee of similar size, which produces only 9 mm³ of pollen per flower and 2-4 µl of nectar per flower (Cane and Payne 1988). A *C. pepo* flower produces 60 times the pollen and 15 times the nectar as a blueberry flower (Cane et al. 2011). Squash and pumpkin blossoms are highly attractive to many pollinators. However, the pollination requirement for some varieties of *C. pepo* can be very high, needing several visits where pollen is deposited to set full fruit. Because of this, *C. pepo* requires a highly efficient pollinator to receive adequate pollination.

1.5.3 Pollination efficacy of *P. pruinosa*

Several studies have been conducted with regards to the pollination efficacy of *P. pruinosa* compared to *A. mellifera*. Differences in the foraging habits of *A. mellifera* and *P. pruinosa* result in less effective pollination by honeybees because they tend to linger in the same flower or on the same plant for longer periods of time, while *P. pruinosa* visits
more flowers per time unit and likely transfers more pollen (Tepedino 1981). Male squash bees are likely responsible for two-thirds of squash plantings’ pollination since the males are highly abundant, often out-numbering females within populations, and their mate-seeking strategy lends itself to visiting many male and female blossoms sequentially (Cane et al. 2011).

One visit by a pollinator is insufficient for the pollination of summer squash, zucchini, or pumpkin and additional visits by bees beyond the minimum number needed for fruit set improves fruit weight substantially (Cane et al. 2011; Tepedino 1981; Jaycox et al. 1975). Within the first hour after sunrise, male squash bees accumulated the seven sequential visits necessary for maximum fruit set and growth in summer squash (Cane et al. 2011). Similar to Tepedino (1981), Cane et al. (2011) found that *C. pepo* plantings were pollinated exclusively by *P. pruinosa* before other species, such as honeybees, had even begun to forage. If *P. pruinosa* populations are large and healthy, bringing in *A. mellifera* for pollination services is unnecessary in squash and pumpkin crops (Tepedino 1981).

However, in some locations, there seems to be insufficient populations of *P. pruinosa* for adequate crop pollination. Walters and Taylor (2006) found that while fruit number was not affected, without the addition of honeybees to squash and pumpkin production fields, there were lower fruit weights and lower seed set. Conversely, a separate study found that farms with honeybee colonies did not have more honeybees per flower than farms without honeybee colonies, indicating that additional honeybee colonies may not lead to better pollination (Schuler et al. 2005).
Since pumpkins are generally sold on a per weight basis, and pumpkin weight is partially a function of seed set, inadequate pollination can decrease profits for growers. To ensure adequate pollination at least cost to farmers, management practices should be employed which are benign to pollinators and that increase the survivorship and abundance of wild bees. Protecting and enhancing services performed by wild pollinators may have a greater impact than bringing in honeybees for improving pollination.

1.5.4 Previous study of *P. pruinosa* nesting

Since the squash bee is a ground-nesting species that inhabits areas in and around *C. pepo* crop fields, conserving its nesting resources may be critical to maintaining robust populations for pollination services. Studies investigating bee nesting can be tedious and difficult to conduct. However, two previous studies of this nature have been conducted and serve as models for the experimental design of this study. Both studies addressed how farming management practices affect squash bee populations. The first, conducted by Schuler et al. in 2005, found that farms that practiced a no-till management strategy hosted three times the density of squash bees as farms that employed tillage practices. This indicates that tillage has a negative impact on squash bee populations, possibly by destroying nests. However, the direct impact of mechanical tillage on squash bee nests was not measured, so impacts on squash bee populations could be a result of other differences associated with conventional tillage versus no-till production systems.

Researchers were unable to identify the exact mechanism of how tillage may harm squash bee larvae present in nests. They suggest that though some larvae may be placed below tillage depth, the collapsing of tunnels above the actual nest may be enough of a disturbance to interfere with emergence (Schuler et al. 2005).
In a later study conducted inside a screenhouse by Julier and Roulston (2009) no negative effect of tillage on squash bee nesting was found. Instead, a negative effect of soil clay content and a positive effect of irrigation on nesting preference were discovered (Julier and Roulston 2009). Even though *P. pruinosa* did not prefer non-tilled soil to tilled soil, this study did not measure the direct impact of mechanical tillage on squash bee nests either to see if this affected emergence the following year. To date there hasn’t been any investigation of a tillage effect on squash bee nests and squash bee emergence. Although, researchers agree that all or a portion of brood cells would be destroyed by tillage because nests generally occur at between 9 to 69 cm below the soil surface (Hurd et al. 1974), which is at or below tillage depth (Schuler et al. 2005; Julier and Roulston 2009). The finding that these bees prefer moist soils may prove important if bees also prefer to nest where mulches that conserve soil moisture are placed. Furthermore, higher soil moisture may regulate soil temperature due to the high specific heat of water (Julier and Roulston 2009). This could provide a more hospitable environment for developing bee larvae by decreasing exposure to temperature extremes (Julier and Roulston 2009). The extreme, high temperatures sometimes reached in the soil beneath black plastic may also be inhospitable for ground-nesting bees and could cause damage to developing bee larvae (Julier and Roulston 2009), however, this remains to be investigated.

1.6 Motivation for research

Given increased demands for fruit and vegetable crops, increased interest in urban agriculture, and concern over using more sustainable farm management practices, including the conservation of pollinators, I have chosen to focus my research on the effects of mulches created from municipal waste materials on squash and pumpkin
performance. Squash and pumpkin are especially benefited by the presence of their specialized, wild pollinator. The highly specialized squash bee is solely dependent on its host, which, for the most part, exists only within an agricultural setting. Thus, farm management practices, especially weed control via tillage, may have a large impact on the survival and abundance of this valuable pollinator, although more research on the direct impacts of tillage on nesting still is needed. With this research project, I wanted to better understand how using mulches influences the nesting and foraging of *P. pruinosa* while also providing sufficient weed control and adequate pollination for the crop.

To look at direct effects of various mulch materials on bee nesting and foraging, an experiment was conducted to track the nesting preference of *P. pruinosa* when offered bare soil versus soil covered with different mulch materials. Fruit pollination of the experimental plots was monitored to see if the mulch materials had any influence on foraging activity of *P. pruinosa*.

Indirect effects of the mulches on bee survival via their effect on floral resources were also considered. A greenhouse study was designed to test the hypothesis that mulch materials alter the quantity and quality of nectar and pollen resources produced by the crop plant. This research was conducted to isolate the impact of the mulch materials on soil moisture and nutrient acquisition without influencing soil temperature, which can be dramatic in the field. In comparing this with field data collected we may better understand what influences differences in foraging between mulch types.

Another aim of this research was to investigate the ability of municipal waste materials to be used as mulch materials. To determine how well individual mulch materials suppressed weed emergence, I conducted an experiment comparing the weed
suppressive ability of both cellulosic and vegetative waste material mulches to the industry standard, black polyethylene plastic. Soil characteristics along with crop yields were also monitored and compared between treatments to better understand how the mulches influenced crop performance. The goal of this research was to develop an alternative weed management strategy for use in *C. pepo* that has application within urban agriculture, is cost effective for growers, safe for pollinators, and has a positive impact on crop performance.

1.7 References


1.8 Tables and Figures

Table 1.1 Comparison table of cited mulch characteristics.

<table>
<thead>
<tr>
<th>Mulch Type</th>
<th>Sheet/Particulate Mulch</th>
<th>Effects on Soil Moisture/Temperature</th>
<th>Known Insect Interactions</th>
<th>Weed Suppressive Ability/Yield Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Bare Soil</em></td>
<td>N.A.</td>
<td>N.A.</td>
<td>N.A.</td>
<td>None</td>
</tr>
<tr>
<td><em>Polyethylene</em></td>
<td>Sheet</td>
<td>Conserves moisture beneath, increases runoff from above; Increases temperature (Tamara 2000; Rice et al. 2001)</td>
<td>Fewer pests (Szendrei 2010)</td>
<td>100% Efficacy (Cirujeda et al. 2012)</td>
</tr>
<tr>
<td><em>Black Plastic</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Chipped Wood</em></td>
<td>Particulate</td>
<td>Conserves moisture; Decreases temperature Fluctuations (Gruda 2008)</td>
<td>Increased insect abundance (Jordan 2004)</td>
<td>Increased crop yields due to weed suppression (Gruda 2008)</td>
</tr>
<tr>
<td><em>Fiber</em></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Shredded Newspaper</em></td>
<td>Tangle of long, skinny paper Strips</td>
<td>Decreases temperature (Grassbaugh et al. 2004)</td>
<td>Unknown</td>
<td>Comparable to black plastic (Grassbaugh et al. 2004; Sanchez et al. 2008; Pellett and Heleba 1995)</td>
</tr>
<tr>
<td><em>Shredded Newspaper+Grass Clippings</em></td>
<td>Combination of two unique particulate Materials</td>
<td>Unknown</td>
<td>Unknown</td>
<td>Unknown</td>
</tr>
</tbody>
</table>
Figure 1.1 Diagram of *Peponapis pruinosa* nest site (adapted from Rozen 1987 and Mathewson 1968).
CHAPTER 2

Mulch Effects on Squash (*Cucurbita pepo*) Floral Resources and Fruit Production and on Pollination and Bee Nesting by *Peponapis Pruinosa*

Abstract

Field and greenhouse studies were conducted in 2011 and 2012 to determine the effects of polyethylene black plastic, woodchips, shredded newspaper, a combination of shredded newspaper plus grass clippings (NP+grass), and bare soil on soil characteristics, *C. pepo* pollination and fruit production, and *P. pruinosa* nesting. Woodchips, shredded newspaper, and NP+grass mulch decreased soil temperature fluctuations while newspaper mulch had greater soil moisture content than woodchip, plastic, or bare soil. Unmarketable, misshapen fruits occurred more frequently in black plastic than in the other mulch treatments. However, no measurable differences in floral resource production or crop pollination were found among mulch treatments, suggesting that misshapen fruits resulted from high soil temperatures experienced in black plastic plots. Nests of the *Cucurbita* specialist bee, *P. pruinosa*, were located within bare, newspaper, and NP+grass plots, so *P. pruinosa* nesting was not prevented by these mulches. NP+grass mulch had a positive effect on plant growth and fruit production presumably from an addition of plant-available nitrogen. Shredded newspaper when combined with grass clippings performed as an effective mulch material that positively affected crop performance with no apparent negative impacts on *P. pruinosa* nesting or on *C. pepo* pollination.
2.1 Introduction

Soil tillage is considered the most energy-consuming of all agricultural field operations (Chauhan et al. 2012). In addition to the cost of fossil fuels used to run machinery used for tillage, the time and labor required for tillage are also significant costs to farmers. The advent of herbicides has greatly reduced the need for tillage (Gianesse and Reigner 2007), but has generated new and different problems, namely herbicide resistance (Powles and Yu 2010). Herbicides also have a direct negative effect on non-target organisms including beneficial insects. Aside from the ecological risks associated with herbicide use, there has been recent interest in alternative weed control practices for organic growers who rely heavily on mechanical cultivation and/or timely hand weeding in an effort to reduce costs and improve sustainability. Organic, as well as, conventional growers may value an alternative weed control strategy to tillage and mechanical cultivation, since this practice causes soil erosion, the degradation of soil structure and microbial communities, and releases sequestered CO₂ back into the atmosphere (Hobbs and Grupta 2008; Gianesse and Reigner 2007). Due to concerns that the overuse of mechanical or chemical weed management methods may have negative impacts on human health and ecological integrity, plus added costs of time and labor for growers, more sustainable weed control practices are needed to mitigate these effects while still maximizing yield (Liebman 2001).

The use of mulch to suppress weed growth by providing a physical barrier may reduce the need for mechanical and chemical weed control in areas where environmental quality and soil conservation are of particular importance. Mulching has proved effective for weed control in fruit and vegetable crops with the added benefit that it limits
potentially harmful chemical exposure to beneficial insects, such as pollinators. A wide variety of mulch materials have been studied, including but not limited to, plastic film, wood fiber, paper, and living or killed plant residues, but many novel mulch materials remain to be investigated with regard to their ability to suppress weeds and improve crop yields. It will also be important to investigate the effects of mulches on beneficial insects, such as crop pollinators, to ensure their overall positive effect on crop management.

While crop pollinators stand to benefit from reductions in herbicide use and tillage operations, pollinators that utilize agricultural fields for nesting deserve individual consideration. One such pollinator is the squash bee, *P. pruinosa*, a major pollinator of the genus *Cucurbita* (squash, pumpkins, and gourds). Oligolectic, or specialist, bee species are thought to be relatively simple to study because the resources available to the bees are easy to calculate and the foraging bees are easy to locate on their host plant (Roulston and Goodell 2011). Farms with consistent management practices also provide a good study environment since current generations of bees have developed from the resources that were available to the previous generation (Roulston and Goodell 2011). It is for these reasons that the squash bee, *Peponapis pruinosa*, and its host plant, *Cucurbita pepo* are good candidates for study. *Peponapis pruinosa* tends to nest directly in crop fields (Julier and Roulston 2009) and weed management strategies used within squash fields could directly impact the population of squash bees present. A decrease in the abundance of this wild, native pollinator may cause pollen limitation needed for fruit production in some cases since *C. pepo* has a relatively high pollination demand (Walters and Taylor 2006, Julier and Roulston 2009). Having a lack of wild, native pollinators
could also raise production costs for growers if they needed to stock honeybee colonies during the relatively long *C. pepo* flowering season.

*Peponapis pruinosa* is expected to show high sensitivity to insecticide application and to tillage since it nests within the fields of its host plant and has no non-crop host plants in most of its range (Hurd et al. 1974) linking its lifecycle to agricultural fields. *Peponapis pruinosa* places the greatest density of its brood cells from 16 to 30 cm deep (Mathewson 1968), which overlaps with some tillage depths, therefore some or all of the bee’s subterranean nests may be destroyed with tillage. The survival and abundance of other native pollinators depends upon the availability of food and nesting resources within foraging range of each other, not just the absence of insecticide. Herbicide application, though it may not directly kill bees, may cause indirect harm by decreasing floral abundance on farms, especially insect-pollinated flora (Holzschuh et al. 2008). These plants provide additional foraging resources for the bees while the crop is not in bloom and thus play a role in supporting wild bee populations (Holzschuh et al. 2008). Although *P. pruinosa* only collects pollen from *Cucurbita* spp., it has been known to collect nectar from other floral hosts (Goodell, personal communication).

While the use of mulch for weed control promises to alleviate some of the incidental risks posed by herbicides and tillage, it could also alter important aspects of pollinator habitat with consequences for *P. pruinosa* populations and crop pollination. Mulch applied to the soil surface acts as a physical barrier to weed emergence and alters the soil microclimate to impede weed seed germination. Similarly, it could be a physical barrier that prevents bees from burrowing in the soil under crop plants. The way in which
mulch alters the soil microclimate may positively or negatively influence nest site preference or larval development (Roulston and Goodell 2011).

Mulches, through their effects on the soil microclimate, may also affect resource allocation patterns of plants with effects not only on fruit maturation, but also on the production of floral rewards gathered by bees including nectar and pollen (Fig. 2.1). Nectar quantity and composition varies widely due to environmental factors such as temperature, soil moisture, and humidity (Fahn 1979; Cruden et al. 1983; Wyatt et al. 1992). Mulches that decrease water infiltration may cause a decrease in the amount of nectar produced. Mulches that conserve water around the crop plants would likely have the opposite effect. Mulches that immobilize nitrogen because of a high carbon to nitrogen ratio may have an influence on the quality of the floral resources produced. Less available nitrogen may have an effect on the protein content of pollen or the sugar content of nectar due to the limited resources available for allocation towards reproductive tissues. If mulch materials alter the quantity or quality of floral rewards, pollinator visitation and crop pollination may be affected.

The objective of this research was to determine the effect of different mulch materials on floral resource production, pollination, and fruit set of *Cucurbita pepo*, as well as the potential for nesting by its specialist pollinator, *P. pruinosa*. Specifically, I tested the following hypotheses: 1) Particulate mulch materials will decrease soil temperature fluctuation and extremes, and increase soil moisture levels in comparison to black plastic and bare soil. 2) Particulate mulches will be suitable areas for squash bees to nest, whereas black plastic sheet mulch will prohibit squash bees from nesting. 3) Mulches that increase soil moisture will increase the quantity of nectar produced. Further,
those mulch materials that provide labile nitrogen will increase flower number, nectar sugar content, and pollen grain number. 4) Mulches that reduce pollen and nectar abundance and quality will reduce pollination of flowers and be associated with aborted or misshapen, poor quality fruits. These hypotheses were tested by investigating the following parameters: mulch effects on soil characteristics, crop plant growth, floral resource production, pollination and fruit set, and \textit{P. pruinosa} nesting ability.

Experiments were carried out over the course of two growing seasons and included a greenhouse study.

\subsection*{2.2 Materials and Methods}

\textbf{Study system}

\textit{Cucurbita pepo} is monoecious and requires pollen to be transferred from it separate male to female flowers. It has a particularly high pollination demand for good fruit set to occur. Each flower is open for one day, opening between 6 and 7 am and closing at approximately noon (Tepedino 1981, Nepi, Pacini and Willemse 1996). Also, for optimum seed set and fruit diameter, female squash flowers must be visited from seven to over twelve times depending on the variety and the bee species that visits (Walters and Taylor 2006, Julier and Roulston 2009). The native pollinator \textit{Peponapis pruinosa} is an efficient pollinator of squash, having evolved closely with \textit{Cucurbita} spp. its biology and life cycle is tightly linked to its host plant. The males have a matinal foraging schedule that overlaps with the early morning bloom of \textit{Cucurbita} flowers. Although many farmers bring in European honeybee hives for pollination of their squash and pumpkin fields, \textit{P. pruinosa} can preempt other bees at the flowers, often collecting
most of the pollen and performing most of the pollination before honeybees begin to work the flowers (Williams et al. 2009; Tepedino 1981; Cane et al. 2011).

*Peponapis pruinosa* is a solitary, ground-nesting bee that produces one generation per season (Williams et al. 2009) (Fig. 2.2). The females make one to several nest hole(s) in the soil throughout the season, where they deposit their eggs and provision solely with *Cucurbita* pollen (Fig. 2.3). In June of the following year in Ohio, USA, the next generation of bees emerges from the previous years’ nest sites (Williams et al. 2009). Female squash bees visit male flowers in search of nectar and pollen to provision their nests and female flowers for nectar to feed on. Male squash bees visit male and female flowers to feed on nectar and to mate with females. Males also sleep in the closed flowers (Schuler et al. 2005) while females return to their below-ground nest once squash blossoms close at midday. Female *P. pruinosa* prefer to nest directly under the squash and pumpkin plants from which they are foraging and in irrigated soils with low clay content (Roulston and Goodell 2011).

**Mulch materials**

The same mulch materials were used for all experiments. Mulch treatments were chosen to include a synthetic material: black plastic film, and biodegradable cellulosic materials that differ between each other in their physical characteristics and which are frequently available municipal waste materials: woodchips, shredded newspaper, and a combination of newspaper and grass clippings (NP+Grass). Polyethylene plastic, 0.032 mm thickness (Hummert International, Earth City, MO, USA) was used as the plastic mulch. Composted hardwood woodchips comprised of mixed species were used. Newspaper was obtained from a local newspaper printing facility in Newark, Ohio.
Glossy inserts were removed and all newspapers were printed with soy-based ink. The newspaper material was shredded into long strips, 1.6 cm wide by approximately 30 cm long, and baled by a document shredding company. Fresh grass clippings were obtained from the Columbus Crew soccer stadium. The clippings from the Columbus Crew were a mixture of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) that were mown on a daily basis. The fungicides applied to the grass on the week of collection in 2011 were chlorothalonil (tetrachloroisophthalonitrile), pyraclostrobin (carbamic acid, [2-[[1-(4-chlorophenyl)-1H-pyrazol-3-yl]oxy]methyl]phenyl)methoxy-, methyl ester), triticonazole, and mefenoxam ((R)-2-[(2,6-dimethylphenyl) methoxyacetylamino] propionic acid methyl ester). Fertilizer, 6-0-1 NPK at a rate of 2.24 kg per ha and glyphosate herbicide (N-(phosphonomethyl) glycine in the form of its isopropylamine salt) were also applied to the grass in 2011. Two fungicides were applied to the grass in 2012, thiophanate-methyl fungicide (dimethyl 4, 4’-o-phenylenebis[3-thioallophanate]) and mono- and dipotassium salts of phosphorous acid. A 14-0-0 NPK fertilizer was also applied to the grass at a rate of 2.34 liters per ha during the week of collection in 2012. In the field experiments, grass clippings were mixed with shredded newspaper and applied to plots within 1-7 days of being cut.

**Crop pollination and bee nesting field study.**

To study crop pollination and bee nesting by *P. pruinosa*, field experiments were conducted inside mesh screen enclosures (hereafter, screenhouses) in 2011 at the Ohio State University Waterman Agricultural and Natural Resources Laboratory (WANRL), Columbus, Ohio (40.00° N, 83.02° W) and in 2012 at The Ohio State University, Newark
The location of the experiment was changed from year one to year two to achieve greater bee survival and nesting. The 6.1 by 6.1 by 2.1 m screenhouse used for experiments conducted in 2011 may have been too small for bees to forage and nest normally. A larger, 9.1 by 4.6 by 6.1 m screenhouse was used for experiments during 2012. A similar screenhouse was used successfully in previous research on *P. pruinosa* nesting (Julier and Roulston 2009).

Soil types were a Crosby silt loam soil (fine, mixed, mesic Aeric Ochraqualfs) at WANRL and a highly amended Glenford silt loam soil (fine-silty, mixed, superactive, mesic Aquic Hapludalfs) at the Newark site. The WANRL site had been previously cropped in winter squash and was sprayed with glyphosate (N-(phosphonomethyl) glycine in the form of its isopropylamine salt) at 2.8 kg per ha with 2% ammonium sulfate (on a per volume basis) in May prior to tillage to clear the field of Canada thistle (*Cirsium arvense* (L.) Scop.). In 2011, plots were sprayed again with glyphosate 2.4 kg per ha with 2% ammonium sulfate (on a per volume basis) to clear plots of weeds that had emerged after tilling, but before mulches were applied. The raised beds at the Newark site had been previously cropped in native wildflowers and volunteer weeds. The raised beds were cleared by hand-pulling plants and lightly hoeing the soil to achieve a level seed bed. The cultivar ‘Dunja’, a 45 day, medium vigor, dark green zucchini with intermediate resistance to powdery mildew and resistance to watermelon mosaic potyvirus, zucchini yellow mosaic potyvirus, and papaya ringspot potyvirus was used for both years of experiments.

Plants were started in the greenhouse and three week-old seedlings were hand-transplanted into plots after being hardened off under shade cloth. No pest or disease
management was used inside the enclosures and industry standard fertilization practices were used (Marr et al. 2004). Two week-old zucchini seedlings were fertilized with 20-10-20 NPK at a rate of 56 kg per ha and with a high phosphorus 9-45-15 NPK fertilizer at a rate of 200 ppm when seedlings were transplanted at three weeks. Plants were side-dressed three weeks after transplanting with 20-10-20 NPK at a rate of 34 kg per ha when they began to bloom. Overhead irrigation was provided as needed during both years of the study.

Treatments were replicated seven (2011) or eight times (2012) and arranged in a completely randomized design (2011) or in a randomized complete block design (2012). Plot dimensions were 91 by 91 cm in 2011 and 55 cm by 122 cm in 2012 with each plot containing a single zucchini plant resulting in 35 plants (2011) or 40 plants (2012) within the screenhouses. An additional 30 potted zucchini plants were provided in 2012 to supply ample nectar and pollen resources. *Peponapis pruinosa* individuals were caught by hand in vials from nearby *Cucurbita* plantings and introduced into the screenhouses over a period of several weeks beginning mid-June and ending mid-July. In 2011, a total of 50 female and 13 male squash bees were introduced into the screenhouse by July 13. In 2012, 35 females and 5 males were introduced into the screenhouse by July 6. Due to minor bee mortality observed in the screenhouse, an additional 6 female and 5 male bees, were introduced on August 3, 2012.

Mulch application and zucchini planting dates were June 14, 2011 and June 11, 2012. In both years, a bare, un-mulched treatment served as a control. Control plots were left bare and weeds were permitted to grow in 2011, but were pulled by hand in 2012 to make locating nests easier. Woodchip, newspaper, and NP+grass mulches were applied to
the soil surface at a thickness of 5 cm. The newspaper, newspaper and grass, and woodchip treatments were applied using 2.56 L plastic buckets, so they could be applied on a volume per area basis. One and a half buckets of material were used to mulch each plot, which equals an application rate of 150 Mg per ha for the woodchips, 55 Mg per ha for the shredded newspaper, and 50 Mg per ha for the NP+grass mulch. The newspaper and NP+ grass treatments were mixed in buckets with holes drilled in the bottom. Approximately 20 L of water was applied to the mulch materials and then mixed by hand until most of the water had drained from the buckets. The mixed materials were applied wet to the soil surface. This process was carried out in an attempt to achieve some degree of hydroentanglement, which is a procedure used to bind fibers (Rawal et al. 2007; Xiang and Kuznetsov 2008). In a preliminary study using shredded newspaper combined with various plant residues, this process improved the strength and integrity of the mulch (see Appendix A). The newspaper and grass treatment consisted of a 2:1 ratio of newspaper to grass clippings on a per volume basis.

To determine soil temperature and soil moisture, weekly measurements were taken in each plot at solar noon from June (2012) or July (2011) through August in both years. One reading per plot per week was taken for both soil temperature and moisture. Soil temperature was measured using a soil thermometer at a depth of 8 cm. Volumetric soil water content was measured using a Delta-T Devices Theta Probe type ML2x portable soil moisture meter. The moisture probe measured volumetric soil moisture at a depth of 10 cm below the surface of the soil. Both the soil thermometer and soil moisture probe were inserted beneath the mulch materials so that measurements were taken at the same soil depth for all treatments. Additionally, meteorological data for precipitation and
air temperature were collected from a weather station located within 0.5 km of the study site in 2011 and approximately 55 km from the study site in 2012.

Mulch effects on plant growth were assessed by taking plant volume measurements in 2011 and 2012 using a measuring tape placed at the soil surface to the extension of the top-most leaf to measure height and placed from one outside leaf to the opposite outside leaf to measure width. Plant volumes were measured on July 26 and August 18, 2011 and on June 27, July 13, and August 22, 2012. SPAD meter readings were taken using the Minolta SPAD-502 Plus chlorophyll meter (Spectrum Technologies, Plainfield, IL, USA) in 2012 to estimate leaf chlorophyll content. Leaf chlorophyll content is correlated with nitrogen content (Loh et al. 2002). SPAD meter readings were taken on July 16 and August 22, 2012 by taking an average of three readings each on a young leaf close to the meristem of the plant, a mid-aged leaf, and an older leaf near the base of the plant.

Crop pollination was assessed by measuring fruit diameter of zucchinis five days after bloom from July through August after squash bees had been introduced into the screenhouses. Fruit diameter is highly correlated with fruit weight and seed set, which, in turn, is correlated with the number of ovules that have been successfully pollinated (Cane, Sampson and Miller 2011). Open female flowers were marked during mornings three days a week and fruit diameter was measured using digital calipers placed 8 cm from the stigmatic end of the fruit 5 days later. Fruit shape was also assessed by categorizing fruits as normal, misshapen (either bulbous or shrunken end), or aborted (Fig. 2.4). Misshapen and small, aborted fruits occur due to inadequate pollination and are not marketable (Delaplane and Mayer 2000). To estimate floral production and fruit
yield per plot, flower and fruit number were recorded throughout the growing season until total flower and fruit production had slowed to less than 5 flowers/fruits per day.

Bee nesting activity was measured during the 2012 field season by observing plots within the Newark screenhouse for 5 minutes per replicate block every three days from July 11 to August 23, 2012. Soil beneath and around the zucchini plant in each plot was examined and when a bee was spotted landing on the ground surface, it was tracked until it entered its nest. The nest was then marked with a flag and mapped. Nesting was measured in a similar manner during the 2011 season, however, no nests were located within the screenhouse at WANRL in Columbus, OH.

**Floral resources greenhouse and field studies**

The effect of mulches on *C. pepo* pollen and nectar production was investigated in a greenhouse and field study. The greenhouse experiment was conducted from January through April 2012 at The Ohio State University Kottman Hall greenhouse. The zucchini cultivar ‘Raven’, a suitable variety for greenhouse production (Shaw & Cantliffe 2005), was seeded on January 23 and 5 week old seedlings were transplanted into 11.4 L polyethylene nursery pots 25 cm in height and 25 cm in diameter on February 23, 2012. The pots were mulched with a single sheet of black polyethylene plastic, a 5cm thick layer of shredded newspaper, or left bare. A mixture of 85% pine bark, 10% composted sewage sludge, and 5% pea gravel was used as the potting medium. The treatments were replicated ten times and arranged in a RCBD with one pot containing one of the three mulch treatments and a single zucchini plant. The pots were fertigated with 20-10-20 NPK at 200ppm using in-pot emitters for two minutes each day. Supplemental lighting was used to expose the zucchinis to a 14 hour photoperiod.
Daily flower production was measured from March 13 to April 28, 2012. Pollen was collected pre-dawn by removing the anthers with scissors and suspending them in vials containing five mL 70% ethanol. The samples were sonicated for two minutes and anthers were then rinsed with an additional five mL 70% ethanol to dislodge any remaining pollen grains. Anthers were then discarded. After letting pollen settle to the bottom of the vials, 8 mL of ethanol were removed using a micropipette and 5 mL of glycerol were added to suspend pollen evenly in solution for counting. Four 20 µL subsamples of the pollen sample were counted using a hemacytometer at 4 X magnification (Das Gracas Vidal et al. 2006; Roulston, Cane, and Buchmann 2000). Nectar was collected from female flowers between 9 and 10:30 am. Samples were taken by inserting a volumetric Hamilton syringe into the nectary and withdrawing all available nectar. Nectar volume was determined by reading the volume collected in the syringe to the nearest 0.5 µL.

The field study was conducted at WANRL in 2012. Samples were collected from pumpkin, cultivar ‘Cannonball’, grown in an open field setting from an experiment comparing the same mulch treatments (refer to chapter 3 for complete details of this study). Three pollen samples and one nectar sample were collected per week from four randomly selected flowers on randomly selected plants within each treatment plot consisting of ten pumpkin plants. Pollen samples were collected in the same manner as the greenhouse experiment. This was done between 5 and 6am before bees had begun to forage for the day.

Nectar was collected from male flowers that were bagged with white, breathable fabric bouffant caps (Cellucap, Philadelphia, PA, USA) secured around the base of the
flower pre-dawn to exclude any visitation by pollinators and removal of nectar. Nectar was collected only from male flowers to not skew harvest data also collected from this experiment (see chapter 3). Samples were collected between 11 am and noon to allow for maximum nectar accumulation (Nepi, Guarnieri & Pacini 2001) so that enough nectar was collected to also take total sugar content measurements. Samples were taken in the same manner as in the greenhouse experiment, however, the nectar collected was expelled from the Hamilton syringe onto an ATAGO pocket refractometer PAL-1 to obtain a brix reading as an estimate for total sugar content of the sample (Fig. 2.5). Sugar concentration was measured as % Brix, which is the number of grams of sucrose per 100 g solution (Corbet 2003).

**Statistical analyses**

Data for the crop pollination and bee nesting field experiments conducted in 2011 and 2012 were analyzed separately for the dependent variables: soil moisture and temperature, plant growth, and fruit production parameters due to different experimental designs between years. Data were also analyzed separately for the 2012 floral resources greenhouse and field experiments. For both studies, all data were subjected to analysis of variance (ANOVA) using the PROC GLM procedure for a completely randomized design (2011 crop pollination field experiment) and the PROC MIXED procedure in SAS for a randomized complete block design (all 2012 field and greenhouse experiments) with blocks as a random effect and treatment as a fixed effect (Statistical Analysis System version 9.3 for Windows™; SAS Institute, Cary, NC). Plot within sampling date was designated as a random effect and plot was also designated as the subject on which repeated measures were taken for soil temperature and moisture. Unstructured covariance
was specified in the model. Differences among least squares treatment means were determined using pairwise t-tests implemented by the PDIFF option with a comparisonwise error rate of alpha = 0.05 (Littell et al. 2006). When the PROC GLM procedure was used treatment means were compared for significant differences according to Fisher’s LSD.

2.3 Results

Pollination and bee nesting study.

Soil Moisture and Temperature. The weather encountered during 2011 and 2012 was dramatically different. 2011 was wetter than average with precipitation totaling 30 cm from June through August (Fig. 2.6). Total precipitation during 2012 was 16 cm with the 30-year average being 33 cm between June and August. During the 2011 field season, no irrigation was needed, however in 2012, plots were irrigated every three days during the early part of the season to avoid water-stressing the plants.

Soil moisture differed between treatments, but also differed between years. In 2011, volumetric soil water content under black plastic had the lowest soil moisture and newspaper had the greatest soil moisture (P < 0.001) (Table 2.1). There was no difference in soil moisture beneath woodchips, NP+grass, and bare soil which all had intermediate soil moisture levels. In 2012, the treatment with the lowest soil moisture was bare soil. Plastic and woodchips treatments had slightly greater volumetric soil water content than bare soil, but, did not differ from each other. Newspaper and NP+grass treatments had the highest soil moisture compared to the other treatments (P < 0.001) (Table 2.1).
Soil temperature also differed between treatments and between years. In 2011, plots with plastic mulch had the highest average soil temperatures, followed by bare soil and the NP+grass treatments, and finally by woodchips and newspaper, which had the lowest soil temperatures ($P < 0.001$) (Fig. 2.7). There was a difference of about two degrees Celsius between newspaper and plastic on some dates. In 2012, there was a significant date by treatment interaction, but at all dates, plastic and bare soil plots had the highest soil temperatures ($P < 0.001$) (Fig. 2.7). Woodchips, newspaper, and NP+grass had similar, lower soil temperatures.

**Plant Growth.** Plant volume differed between treatments and between years. In 2011, plants in plastic, NP+grass, and bare plots had the largest average plant volume and plants in woodchip and newspaper had the lowest volumes ($P < 0.05$) (Table 2.2). In 2012, NP+grass plots produced plants with the largest plant volumes, followed by plastic ($P < 0.001$) (Table 2.2). Plots containing the bare, newspaper, and woodchips mulch treatments produced the smallest plants. Similar patterns were seen in plant growth between treatments earlier and later in the season, although differences were more pronounced early in the season during both years.

In 2012, SPAD meter readings displayed differences in leaf chlorophyll content between mulch treatments. Plants grown in the NP+grass, bare, and plastic plots were darker green in color than the woodchip or newspaper treatments, indicating higher leaf chlorophyll content and higher nitrogen acquisition by the plants ($P < 0.001$).

**Pollination and Fruit Production.** In 2011, there were no differences in total fruit number between mulch treatments. However, in 2012, more zucchini fruits were produced by plants grown in plastic and NP+grass plots than in newspaper alone, woodchips, or bare
soil plots \((P = 0.05)\) (Table 2.3). There was no difference in fruit diameter in 2011 or 2012. This indicates that mulch treatments received adequate visitation by \textit{P. pruinosa} for full pollination. Because the fruit shape data were categorical, the percent of total fruit in each category were analyzed. There was no difference in percent of misshapen fruits in 2011. In 2012, there was a higher percentage of misshapen fruits produced by plants in plastic and woodchip treatments, although the percentage was only significantly higher than the percentage of misshapen fruits produced in bare soil plots \((P = 0.05)\) (Table 2.3). Misshapen fruits included both bulbous and shrunken-end fruits, which may indicate poor pollination or environmental effects on fruit development. There were no differences in the number of aborted fruits among mulch treatments in either year (data not shown).

**Bee Nesting.** There were four confirmed nest sites in total. Two of the nests were located within a bare plot, the other two were located in a newspaper plot, and a NP+grass plot (Figs. 2.8 and 2.9). There were insufficient data to conduct a statistical analysis on nesting preference. However, the results suggest that the newspaper and NP+grass mulches do not prevent \textit{P. pruinosa} nesting.

**Floral resources study**

There were no differences in male or female \textit{C. pepo} flower production between plastic, newspaper, and bare soil treatments during the 2012 greenhouse experiment (Table 2.4). Nor were there any differences among treatments in pollen grain numbers in male flowers or in nectar volume of female flowers (Table 2.4). Similarly, in the 2012 field study, there were no differences among treatments in nectar volume of male flowers or in total nectar sugar content of male flowers (Table 2.4). Pollen data from the 2012 field study is presented in Appendix B.
2.4 Discussion

There were differential effects of mulch type on pollinator and crop performance. Certain types of mulch may be more benign to *P. pruinosa*. Three of the mulches tested, woodchips, newspaper, and NP+grass, had an insulating effect on soil temperature. These mulches resulted in a lower average soil temperature than black plastic or bare soil, indicating that the mulches may have kept the soil beneath them from reaching extreme high temperatures during hot summer days. The lower average soil temperature in combination with higher soil moisture levels reported in woodchip, newspaper, and NP+grass mulch support the first hypothesis that particulate mulch materials would decrease extreme fluctuations in soil temperature and increase soil moisture. Little is known about what influences nest site preference for ground nesting bee species, but decreases in soil temperature fluctuation and a lower average soil temperature could benefit *P. pruinosa* by insulating brood cells and developing larvae from temperature extremes (Roulston & Goodell 2011) that could affect development processes or lead to early exiting from the soil when bees may still be vulnerable to a late frost or while there are not enough floral resources available. Additionally, Julier and Roulston (2009) found a positive effect of irrigation on *P. pruinosa* nesting, indicating that they prefer to nest in moist soils. Based on this finding, it may be that *P. pruinosa* would prefer to nest under a mulch material that reduces exposure to temperature extremes and conserves soil moisture.

No inference about *P. pruinosa* nesting preference could be determined due to low nesting densities, so bee nesting preference with regard to mulch materials compared to bare soil remains to be investigated. Nests were found in newspaper and NP+grass
mulches, so from this we can conclude that they did not prohibit nesting. This finding in itself is noteworthy because mulches by design create a barrier over the soil surface, which could be more difficult to burrow through for bees. In addition, there are differences in color and texture, which can influence visual cues used to forage or locate nests, and the barrier of the mulch, which the bees must burrow through to get to the soil (Fig. 2.10). It is possible that the distinctions of color hue used by some bees to navigate through their environment (Gumbert 2000) could lead to a nesting preference within a certain mulch material based on color and light reflectance. Many polyethylene plastic films contain UV-absorbing components to prolong the life of the material, which could influence the flight patterns of insect that use UV-reflectance patterns as cues for recognizing host plants (Costa et al. 2002).

Mulches that increased soil moisture did not increase the quantity of nectar produced as predicted. There was also no effect of mulch type on flower number, nectar sugar content, or pollen quantity indicating that an addition of plant-labile nitrogen, such as what may have occurred with the NP+grass treatment, has little to no effect on floral resources. Previous work demonstrated that increasing soil water levels doubled nectar volumes and sucrose content in two milkweed species, *Asclepias syriaca* and *A. exaltata* (Wyatt et al. 1992). Similarly, *Epilobium canum* (Onagraceae), a hummingbird-pollinated herbaceous shrub, produced approximately 25% less nectar when grown under low water conditions (Boose 1997). Environmental factors, such as soil fertility, have a large impact on the ability of a plant to provision its offspring either by altering flower number and/or pollen production per flower (Delph et al. 1997). *Cucurbita pepo* pollen produced from plants grown on high phosphorous soil differed in its chemical composition from pollen
produced from plants grown on low phosphorus soil (Lau and Stephenson 1994). Pollen grain size can also differ according to growing conditions (Stephenson et al. 1994). The differences in soil microclimate parameters that resulted from the five mulch treatments tested in this study may not have been extreme enough to cause a consistent difference in the floral resources produced by *C. pepo*, especially since plants were irrigated when needed and received ample fertilizer to avoid causing stress to the plants.

There were slight differences in total fruit number between mulch treatments, but this effect was inconsistent between years. Since fruit diameter did not differ consistently between treatments, it can be assumed that pollinator visitation was similar among treatments, or at least did not vary to an extent that influenced fruit quality. Because there were no differences in floral resources among treatments, it is not surprising that there was also no evidence of pollination differences. However, flower choice during foraging was limited because bees were restricted to visiting flowers in the screen house. Pollinator visitation may be better studied in a larger, open field setting to investigate possible differences in visitation between mulch types.

Higher percentages of misshapen fruits were reported within plots mulched with polyethylene black plastic during both years, with a significant effect reported in 2012. Misshapen fruits could result from uneven pollen coverage of the stigmatic surface by pollinators, which might cause different parts of a fruit to develop at different rates. However, it is unclear why uneven pollen deposition would occur more in plastic plots and this idea is generally not supported by previous work. For instance, uniform coverage of the five stigmas within apple blossoms, *Malus x domestica*, was not necessary for full seed development (Sheffield et al. 2005). Another possibility could be that misshapen
fruits developed in plastic mulch, because it created higher soil temperatures in the plants’ root zones. High root zone temperatures have been found reduce water uptake from roots and decrease above-ground biomass (Graves 1991), which might explain fruit deformation due to general plant stress. Another explanation could be that misshapen fruits resulted from the leaching of hydrocarbons from the polyethylene plastic. As plastic degrades various hydrocarbons can leach out of the material especially under hot conditions (Westerhoff et al. 2008). No research to date has been conducted about how these leached hydrocarbons may be taken up by plants or influence plant growth. A similar effect may explain the high percentage of misshapen fruits that occurred in woodchips plot during 2012. Since the source of the chipped wood fiber was unknown, it is possible that chemicals leached from the woodchips may have affected fruit development.

The most likely cause of misshapen fruits may be the effect of heat stress on pollen tube development. Pollen tubes of *C. pepo* extended significantly longer when developed in vitro under 20°C than 30°C (Johansson and Stephenson 1998). This difference in pollen tube development has been shown to have a direct impact on fruit set resulting in unfertilized ovules at higher temperatures in strawberry (Lendesma and Sugiyama 2005). This reduction in pollen tube development may be responsible for misshapen *C. pepo* fruits found in black plastic. Ambient air temperatures reached well over 30°C during both years of the study (Fig. 2.6) and air temperatures in areas where soil was covered with black plastic were likely hotter than other treatment areas due to the heat absorption properties of black plastic.
The NP+grass mulch increased plant volume and led to higher leaf chlorophyll content indicating an addition of plant-available nitrogen. The addition of plant-available nitrogen translated to higher total fruit numbers in NP+grass plots during 2012. This mulch also allowed for *P. pruinosa* nesting and conserved soil moisture while decreasing extreme soil temperatures, which may be beneficial to *P. pruinosa* and *C. pepo* performance. Shredded newspaper mulch when combined with grass clippings has potential for use in *C. pepo* plantings to conserve native pollinator populations and improve crop performance.

Further research is needed to determine *P. pruinosa* nesting preferences regarding mulch type. *P. pruinosa* may prefer to nest under a particular mulch material over bare soil due to mulch’s effects on the soil microclimate. The effect of mulch on crop pollination and fruit production of *C. pepo* should be investigated further as well to determine the exact mechanism causing misshapen fruit. The impact of mulch materials on soil microclimate and on the microclimate directly surrounding crop plants may have a greater impact on fruit shape than on pollinator visitation, which did not differ between the mulch treatments studied. To better understand how mulches may influence floral resource production, effects of mulch should be determined under varying water and nutrient stress conditions to see if certain mulch materials are able to buffer the environmental factors that cause decreases in the quantity and/or quality of nectar and pollen. Future study is necessary to determine the full range and significance of mulch effects on *C. pepo* fruit development and floral resources. Research should continue to be conducted on mulch materials that may increase marketable fruit and vegetable crop yields, reduce costs for farmers, and increase sustainability within local food systems.
2.5 References


2.6 Tables and Figures

Table 2.1 Comparison of least squares means from a linear mixed model of the effects of mulch type on soil moisture in 2011 and 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Mulch Type</th>
<th>Volumetric Soil Water Content (mm$^3$ per mm$^{-3}$)</th>
<th>2011</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td></td>
<td>25.1</td>
<td>b</td>
</tr>
<tr>
<td>Plastic</td>
<td></td>
<td>22.4</td>
<td>c</td>
</tr>
<tr>
<td>Woodchips</td>
<td></td>
<td>27.6</td>
<td>b</td>
</tr>
<tr>
<td>Newspaper</td>
<td></td>
<td>32.3</td>
<td>a</td>
</tr>
<tr>
<td>NP+Grass</td>
<td></td>
<td>25.3</td>
<td>b</td>
</tr>
</tbody>
</table>

*Least squares means within a column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of alpha = 0.05.*
Table 2.2 Comparison of least squares means from a linear mixed model of the effects of mulch type on zucchini plant volume in 2011 and 2012 and on average SPAD values depicting leaf tissue chlorophyll content in 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Mulch Type</th>
<th>Early Plant Volume (m$^3$)$^a$</th>
<th>Mature Plant Volume (m$^3$)$^b$</th>
<th>Average Plant Volume (m$^3$)$^c$</th>
<th>SPAD 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2011</td>
<td>2012</td>
<td>2011</td>
<td>2012</td>
</tr>
<tr>
<td>Bare</td>
<td>10.7</td>
<td>5.1</td>
<td>16.3</td>
<td>9.6</td>
</tr>
<tr>
<td>Plastic</td>
<td>11.4</td>
<td>6.0</td>
<td>16.6</td>
<td>10.7</td>
</tr>
<tr>
<td>Woodchips</td>
<td>5.7</td>
<td>3.8</td>
<td>10.8</td>
<td>7.6</td>
</tr>
<tr>
<td>Newspaper</td>
<td>7.7</td>
<td>5.0</td>
<td>11.6</td>
<td>6.9</td>
</tr>
<tr>
<td>NP+grass</td>
<td>13.1</td>
<td>9.7</td>
<td>19.1</td>
<td>12.7</td>
</tr>
</tbody>
</table>

$^a$ Early plant volumes were measured at 6 WAP in 2011 and 4 WAP in 2012.

$^b$ Mature plant volumes were measured at 9 WAP in 2011 and 10 WAP in 2012.

$^c$ Least squares means within column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of $\alpha = 0.05$. 

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Table 2.3 Comparison of least squares means from a linear mixed model of the effects of mulch type on zucchini fruit number, diameter and the percentage of misshapen fruit during the 2011 and 2012 growing seasons. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Mulch Type</th>
<th>Total Fruit Number</th>
<th>Average Fruit Diameter (mm)</th>
<th>Percent Misshapen Fruit (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>3.7 c</td>
<td>2.0 b</td>
<td>60.8</td>
</tr>
<tr>
<td>Plastic</td>
<td>2.6 a</td>
<td>3.4 b</td>
<td>58.4</td>
</tr>
<tr>
<td>Woodchips</td>
<td>2.3 b</td>
<td>2.0 a</td>
<td>62.9</td>
</tr>
<tr>
<td>Newspaper</td>
<td>1.9 b</td>
<td>2.0 b</td>
<td>54.7</td>
</tr>
<tr>
<td>NP+grass</td>
<td>2.0 a</td>
<td>3.2 a</td>
<td>66.7</td>
</tr>
</tbody>
</table>

a Number of fruit produced per plant for the duration of the growing season.
b Percent misshapen fruit (shrunken and/or bulbous).
c Columns lacking letters indicate no significant treatment effect.
d Least squares means within a column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of alpha = 0.05.
Table 2.4 Comparison of least squares means from a linear mixed model of the effects of mulch type on flower production, pollen quantity, and nectar volume and total sugar content (Brix Percentage) for 2012 greenhouse and field experiments. Mulches included no mulch (bare), black plastic, and newspaper for the greenhouse experiment and no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass) for the field experiment.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Mulch Type</th>
<th>Male Floral Production $^a$</th>
<th>Female Floral Production $^a$</th>
<th>Pollen Grains per Flower</th>
<th>Nectar Volume per Flower (uL)</th>
<th>Brix %$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greenhouse</td>
<td>Bare</td>
<td>18.0</td>
<td>6.8</td>
<td>20836</td>
<td>71.8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>18.5</td>
<td>7.4</td>
<td>24509</td>
<td>69.7</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>18.2</td>
<td>6.5</td>
<td>20209</td>
<td>84.3</td>
<td>-</td>
</tr>
<tr>
<td>Field 2012</td>
<td>Bare</td>
<td>3.4</td>
<td>2.0</td>
<td>-</td>
<td>83.3</td>
<td>34.4</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>3.4</td>
<td>3.3</td>
<td>-</td>
<td>75.9</td>
<td>35.7</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>3.6</td>
<td>2.6</td>
<td>-</td>
<td>105.7</td>
<td>36.4</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>3.5</td>
<td>2.6</td>
<td>-</td>
<td>86.5</td>
<td>36.5</td>
</tr>
<tr>
<td></td>
<td>NP+Grass</td>
<td>3.9</td>
<td>3.6</td>
<td>-</td>
<td>89.1</td>
<td>33.5</td>
</tr>
</tbody>
</table>

$^a$ Floral production parameter represents the total flower production per plot of a single plant throughout the duration of the growing season (January through April, greenhouse study; June through August, field study).

$^b$ Least square means are presented; columns lacking letters indicate no significant treatment effects according to pairwise t-tests with a comparisonwise error rate of $\alpha = 0.05$.

$^c$ Brix Percentage represents the total concentration of all soluble solids in a sample. For floral nectar this value provides an estimate of percent total sugar content (ATAGO manual; Corbet 2003).
Figure 2.1 Conceptual model of the possible effects associated with mulch application and how those effects may influence *P. pruinosa* visitation and *C. pepo* fruit quality and yield.
Figure 2.2 Images of *P. pruinosa* in *Cucurbita pepo* blossoms (Williams et al. 2009).

Figure 2.3 Image of a *P. pruinosa* nest site (Williams et al. 2009).
Figure 2.4 Images depicting fruit shape categories for *C. pepo*. Top: normal fruit shape, Bottom Left to Right: bulbous misshapen fruit, shrunken-end misshapen fruit, aborted fruit.
Figure 2.5 Images depicting nectar collection procedures from a male *C. pepo* flower. A: bagged male flower, B: partially dissected male nectary, C: extraction of nectar from nectary with volumetric Hamilton syringe, D: deposition of nectar onto hand-held refractometer for brix percentage reading of sample.
Figure 2.6 Ohio Agricultural Research and Development Center (OARDC) weather station data from Columbus, OH for the 2011 and 2012 growing seasons. A: daily precipitation July through September 2011, B: daily precipitation June through September 2012, C: daily maximum, minimum, and average air temperature July through September 2011, D: daily maximum, minimum, and average air temperature June through September 2012.
Figure 2.7 Average soil temperature where each line represents a different mulch treatment. Vertical bars represent ± SE. A: 2011 values during July through August, B: 2012 values during June through August.

<table>
<thead>
<tr>
<th>Woodchips</th>
<th>Woodchips</th>
<th>Bare</th>
<th>NP+Grass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>Plastic</td>
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<td>Bare</td>
</tr>
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<td>Newspaper</td>
<td>Newspaper</td>
<td>Newspaper</td>
<td>Newspaper</td>
</tr>
<tr>
<td>Plastic</td>
<td>NP+Grass</td>
<td>NP+Grass</td>
<td>Woodchips</td>
</tr>
<tr>
<td>NP+Grass</td>
<td>Bare</td>
<td>Plastic</td>
<td>Plastic</td>
</tr>
</tbody>
</table>

Figure 2.8 Map of where *P. pruinosa* nests were located during the 2012 field season. Nests are indicated by stars.
Figure 2.9 Image of *P. pruinosa* nest site located within newspaper and grass mulch. Arrow points to nest entrance.

Figure 2.10 Image of cross-section of newspaper mulch at the surface of the soil, indicating the physical barrier of the mulch to weed emergence and to *P. pruinosa* nest excavation.
CHAPTER 3

Weed Suppression in *Cucurbita pepo* by Mulches Composed of Municipal Waste Materials

Abstract

Field studies were conducted in 2011 and 2012 to determine the effects of polyethylene black plastic, woodchips, shredded newspaper, a combination of shredded newspaper plus grass clippings (NP+grass), and bare soil on soil characteristics, weed abundance, pest and disease pressure, and overall crop performance. Woodchip, newspaper and NP+grass mulches conserved soil moisture and NP+grass mulch accumulated the most soil growing degree days over the course of a season. NP+grass mulch had a positive effect on pumpkin plant growth, producing plants greater in size and with higher leaf chlorophyll content than plants grown on bare soil. All mulch treatments resulted in higher pumpkin yield than bare soil, but only plastic, newspaper, and NP+grass mulch resulted in higher numbers of marketable fruits than bare soil. Suppression of weed biomass ranged from 74% by NP+grass to 100% control by black plastic at six weeks after planting in 2011. At the time of harvest in 2011, suppression ranged from 49% by NP+grass to a 89% reduction in weed cover by black plastic compared to bare soil. In 2012, suppression of weed biomass ranged from 99% in woodchips to 100% control by plastic and NP+grass mulch at four weeks after planting. By the 2012 harvest, all mulches resulted in over 99% reduction in weed biomass compared to bare soil. Weed suppression was higher in 2012 for all treatments due to drier weather conditions.
Shredded newspaper and shredded newspaper combined with grass clippings should be considered for further research because of their potential to provide adequate weed suppression and improve crop performance and increase sustainability within urban agricultural systems.

3.1 Introduction

The current population of the United States is 311 million and is projected to grow at an increasingly rapid rate (U.S. Census Bureau, http://www.census.gov). Approximately 80 percent of our population lives in metropolitan areas and most agriculture is considered to be urban or urban-influenced because of its proximity to urban areas (Butler and Maronek 2002). The amount of urban land used for food production must increase because of population growth within urban areas and lack of non-urbanized land available for agricultural production (Lorenz and Lal 2009). Along with increasing urbanization, the consumption of locally grown foods and organic foods has risen sharply in the United States over the past decade. In the past ten years the sale of organic food and beverages has risen from $1 billion to $28.6 billion, with the highest growth occurring in the sale of organic fruits and vegetables (Organic Trade Organization 2011). A recent national survey indicated a consumer preference for local and organic produce over conventionally produced items. Fifty percent of consumers claimed they would choose locally grown produce, 28% would choose organic produce regardless of its origin, and only 9% would choose a conventionally produced product when given a choice of the three (Food Marketing Institute 2008). The growing interest in sustainable local food production has created incentives for crop producers, especially in urban areas,
to grow food for local consumption using low amounts of chemical inputs and sustainable or organic techniques (McCullum et al. 2005).

Weeds represent a major obstacle to organic crop production systems (Walz 1999). For small-scale producers in urban and peri-urban environments, there is a need for organic weed control methods that are inexpensive, sustainable, and accessible. Organic weed management strategies are especially appealing for the urban environment. The close proximity of crop production areas to people and other organisms may preclude the use of chemicals for safety reasons, or the use of tillage because of a lack of space for large-scale, farm equipment. The use of mulch as a physical barrier to weeds has been used with success in numerous fruit and vegetable crops. However, many novel mulch materials remain to be investigated with regard to their ability to suppress weeds and improve crop yields.

The use of mulches reduces the need for tillage or herbicide application by blocking the emergence of weed seedlings around crop plants. Mulches alter the soil microclimate by regulating temperature, moisture, and light conditions for weed seeds and seedlings beneath the mulch material (Teasdale and Mohler 2000). Altering the microclimate that a weed seed encounters can adversely affect seed germination and suppress weed growth by keeping weed seed germination rates low.

Aside from their impact on weed seed germination, mulches also influence a seedling's ability to physically emerge above the soil surface and compete with crops for space, light, water and nutrients. Teasdale and Mohler (2000) demonstrate that the success of a weed emerging through a mulch material depends upon the seedling's ability to grow around the obstructing mulch material under limiting light conditions. Therefore,
the structure of the mulch material, which determines the presence or absence of gaps allowing light and seedling penetration, will determine how well the mulch slows weed emergence. Teasdale and Mohler (2000) determined that mulches that had the greatest proportion of their volume occupied with mulch elements allowed less light to penetrate down to the soil surface. Light deprivation tends to lower weed seedling emergence, but not for all weed species (Teasdale and Mohler 2000), nevertheless weed emergence decreases exponentially as the mass of the mulch applied increases (Teasdale and Mohler 2000).

Polyethylene or polyvinyl plastic film has been used successfully since the 1960s for weed suppression and to induce earlier harvests (Gruda 2008). Plastic mulch is often used in vegetable and fruit production for weed control in both organic and conventional farm operations, and is combined with herbicide and pesticide use on many conventional farms. There are many advantages as well as drawbacks to using plastic mulch for weed control. Black, polyethylene plastic is an impervious material with no gaps in its solid sheet. This makes it very effective at controlling weeds, often achieving 100% efficacy of control.

Although, black polyethylene plastic is highly effective at controlling weeds, there are some disadvantages to using plastic films. Plastic film is often impervious to water, which can impede water infiltration and increase water runoff. In situations where black plastic is used in combination with chemical application, this could lead to off-site loading of herbicides and pesticides, which can have negative environmental and human health implications (Rice et al. 2001). Black plastic mulch can cause overheating in warmer climates or during hot weather in the summer, which can be detrimental to
growth of some crops (Gruda 2008). Furthermore, using plastic film as mulch requires specialized equipment for application and added time for removal of the material since it does not degrade in the field (Díaz-Pérez and Batal 2002). Additionally, the disposal of polyethylene film has enormous ecological costs. As of 1995, around a hundred million kg of agricultural plastic are either landfilled or burned each year (Anderson et al. 1995) and this figure has most likely increased in recent years.

Shredded newspaper mulch is a biodegradable alternative to black plastic which may be more effective at controlling weeds than sheet newspaper, which is prone to ripping and tends to degrade too rapidly (Shogren 2000). Several studies have demonstrated adequate weed suppression using shredded newspaper mulch, comparable to that of black plastic (Grassbaugh et al. 2004; Pellett and Heleba 1995; Sanchez et al. 2008). Using recycled paper has the advantages of providing a new market for a waste material, conserving resources, and sparing landfill space (Anderson et al. 1995). Recycled newsprint is a resource available in large quantities especially in and around urban centers (Paper Industry Association Council 2007). In the past, there has been concern about the carbon-based ink used for printing on newspaper, which contains polycyclic aromatic hydrocarbons (PAHs). PAHs are known human carcinogenic compounds that when applied to land and allowed to build up in soil could be unsafe (Anderson et al. 1995). However, in recent years, most, if not all, newsprint has switched to soy-based ink (Anderson et al. 1995). Land applying newsprint no longer poses a threat to human health or environmental quality and is acceptable under organic certification as long as there are no ‘glossy’ paper contaminants (USDA 2008).
One challenge with using paper as a mulch material is nitrogen immobilization. Non-composted recycled paper products have a C:N ratio of approximately 500:1 (Edwards 1997; Glenn et al. 2000). When materials high in carbon are added to the soil, microorganisms that feed on carbon-containing materials thrive and deplete the soil of plant available nitrogen by converting inorganic N to organic N, which is generally unavailable for plant uptake (Tahboub and Lindemann 2007). This is a drawback with the use and incorporation of any type of carbon-based mulch material into the soil, but is extremely pronounced with the use of paper. However, there may be ways of ameliorating this problem by combining paper with materials high in nitrogen to achieve a more balanced C:N ratio in mulch. Fresh grass clippings represent a plant residue that is high in nitrogen (Fang et al. 2007). Plant residues tend to be less effective in controlling weeds since they often contain gaps between leaves and stems of the plant residue. However, increasing soil organic carbon through plant residues has positive effects on soil structure and quality (Saroa and Lal 2003) and the added nitrogen may offset the imbalance in C:N ratio caused by paper. Many types of plant residues exist that are suitable for use as mulch materials. Corn stubble, wheat and barley straw, wood fiber chipped from downed trees, municipal leaf waste, and even sheep’s wool, an animal residue, have been used as mulching materials (Duppong et al. 2004).

The objective of this study was to determine the weed suppressive ability of mulches produced from municipal waste materials: woodchips, shredded newspaper, and shredded newspaper plus grass clippings, in comparison to the industry standard, black polyethylene plastic mulch, in pumpkin production. The first hypothesis was that all particulate mulches will decrease soil temperature fluctuation and extremes
and that all particulate mulches will increase soil moisture levels compared to black plastic and bare soil. Woodchip and newspaper mulches will increase the C:N ratio of the soil. The second hypothesis was that all mulches will result in higher pest abundance. The third hypothesis that shredded newspaper and shredded newspaper plus grass clippings would provide comparable weed control and yields to that of black plastic, but shredded newspaper in combination with grass clippings would provide higher yields than other mulch treatments due to additional nitrogen provided by the grass clippings. I also hypothesized that all mulch treatments would yield more marketable pumpkins compared to bare soil. To test these hypotheses field studies were conducted over the course of two growing seasons investigating the following parameters: mulch effects on soil temperature, soil moisture, crop plant volume and nitrogen acquisition, weed density and biomass, and crop yield.

3.2 Materials and Methods

Site Preparation and Experimental Design. Field experiments were conducted on a Crosby silt loam soil (fine, mixed, mesic Aeric Ochraqualfs) at the Ohio State University Waterman Agricultural and Natural Resources Laboratory (WANRL), Columbus, Ohio (40°00’ N, 83°02’ W) from June through September of 2011 and 2012 to determine the effect of mulches on pumpkin production and weed control. The same experiment was conducted in two adjacent fields with similar soil conditions. The field was previously cropped in winter squash in 2010 and in field corn in 2011.

In 2011, plots were sprayed with glyphosate (N-(phosphonomethyl) glycine in the form of its isopropylamine salt) at 2.8 kg per ha with 2% ammonium sulfate per volume in May prior to tillage to control Canada thistle (Cirsium arvense (L.) Scop.). In 2011,
plots were sprayed again with glyphosate at 2.4 kg per ha with 2% ammonium sulfate per
volume to control weeds that had emerged after tilling, but before mulches were applied.
In 2012, the field was chisel plowed and disked one day prior to planting.

The pumpkin cultivar ‘Cannonball’ was chosen because of its powdery mildew
resistance, long shelf life, and 2-3 kg pumpkin size making for numerous flowers on a
bush type plant. During both years, after the fields had been tilled and the mulch
treatments established untreated pumpkin seeds were direct-seeded on June 13, 2011 and
June 12, 2012 at a within-row spacing of 91 cm. An additional single row was planted on
the east and west ends of the field to minimize border effects. Due to poor germination in
some plots both years, plots with missing seedlings were re-planted within a week of the
initial planting date. Industry standard fertilization practices were used (Marr et al. 2004)
and overhead irrigation was provided as needed during both years of the study. Two
week-old pumpkin seedlings were fertilized with a high phosphorus 9-45-15 NPK
fertilizer at a rate of 200 ppm. Plants were side-dressed five weeks after planting with 20-
10-20 NPK at a rate of 34 kg per ha when they began to bloom.

The same mulch materials were used for all experiments. These were black
plastic, woodchips, shredded newspaper, and shredded newspaper combined with grass
clippings (hereafter, NP+grass). Polyethylene plastic, 0.032 mm thickness (Hummert
International, Earth City, MO, USA) was used as the plastic mulch. Composted
hardwood woodchips of mixed species were used. Newspaper was obtained from a local
newspaper printing facility in Newark, Ohio. Glossy inserts were removed from
newspapers and all newspapers were printed with soy-based ink. The newspaper material
was shredded into long strips, 1.6 cm in width and approximately 30 cm in length, and
baled by a document shredding company. Fresh grass clippings were obtained from the Columbus Crew soccer stadium. The clippings from the Columbus Crew were a mixture of Kentucky bluegrass (Poa pratensis L.) and perennial ryegrass (Lolium perenne L.) that were mown on a daily basis. The fungicides applied to the grass on the week of collection in 2011 were chlorothalonil (tetrachloroisophthalonitrile), pyraclostrobin (carbamic acid, [2-[[1-(4-chlorophenyl)-1H-pyrazol-3-yl]oxy]methyl]phenyl)methoxy-, methyl ester), triticonazole, and mefenoxam ((R)-2-[(2,6-dimethylphenyl) methoxyacetylamino] propionic acid methyl ester). Fertilizer, 6-0-1 NPK at a rate of 2.24 kg per ha and glyphosate herbicide were also applied to the grass in 2011. Two fungicides were applied to the grass in 2012, thiophanate-methyl fungicide (dimethyl 4, 4′-o-phenylenebis[3-thioallophanate]) and mono- and dipotassium salts of phosphorous acid. A 14-0-0 NPK fertilizer was also applied to the grass at a rate of 2.34 liters per ha during the week of collection in 2012. In the field experiments, grass clippings were mixed with shredded newspaper and applied to plots within 1-7 days of being cut. Treatments were arranged in a randomized complete block design and were replicated four times. Plot size was 1.2 m by 9.1 m with ten pumpkin plants per plot.

Mulch application and pumpkin planting dates were June 13, 2011 and June 12, 2012. A bare, un-mulched treatment served as an unweeded control. Woodchip, newspaper, and NP+grass mulches were applied to the soil surface at a thickness of 5 cm. The newspaper, NP+grass, and woodchip treatments were applied using 2.56 L plastic buckets, so they could be applied on a volume per area basis. Fifteen buckets of material were used to mulch each plot, which equals an application rate of 150 Mg per ha for the woodchips, 55 Mg per ha for the shredded newspaper, and 50 Mg per ha for the
NP+grass mulch. The newspaper and NP+grass treatments were mixed in buckets with holes drilled in the bottom. Approximately 20 L of water was dumped onto the mulch materials and then mixed by hand until most of the water had drained from the buckets. This process was carried out in an attempt to achieve some degree of hydroentanglement, which is a procedure used to bind fibers (Rawal et al. 2007; Xiang and Kuznetsov 2008).

In a preliminary study using shredded newspaper combined with various plant residues, this process improved the strength and integrity of the mulch (see Appendix A). The NP+grass treatment consisted of a 2:1 ratio of newspaper to grass clippings on a per volume basis.

Several pest control measures were implemented during both years to control striped cucumber beetle (*Acalymma vittatum* F.), spotted cucumber beetle (*Diabrotica undecimpunctata* L.), and western corn root worm (*Diabrotica virgifera virgifera* LeConte), which all belong to the family Chrysomelidae and transmit bacterial wilt, and squash bugs (*Anasa tristis* De Geer). The main control tactic for controlling cucumber beetles was the use of pheromone lure traps to attract the beetles and a fumigant strip for killing the trapped insects. During the 2011 growing season spinozad (a mixture of spinosyn A and spinosyn D), an Organic Materials Review Institute (OMRI) listed insecticide, was sprayed at a rate of 2.91 L/ha on August 9 and August 20 in an attempt to decrease stress due to pest damage, but this treatment was ineffective at controlling the beetles. During the 2012 season, pheromone traps were used in combination with 14 g row covers (Hummert International, Earth City, MO, USA), which allowed 85% light transmittance and 100% air and water penetration. The row covers were kept in place until July 1, approximately a week before flowering began. Row covers were used
because of the high populations of cucumber beetle and high incidence of bacterial wilt encountered during the 2011 field season and the ineffectiveness of spinosad. During 2012, after weekly pest presence was assessed, squash bug eggs were scraped from plants and nymphs and adults found were crushed by hand to decrease crop stress due to insect pressure. As an additional control measure for squash bugs, pieces of plywood were placed in aisles to lure squash bugs there where they could be physically crushed by hand when discovered.

Meteorological data for precipitation and air temperature were collected from a weather station located within 0.5 km of the study site. The Delta-T Devices Theta Probe type ML2x portable soil moisture meter was used to measure volumetric soil water content for each plot on a weekly basis at solar noon. The moisture probe measured volumetric soil moisture at a depth of 10 cm below the surface of the soil. To measure differences in soil temperature, sensors and data loggers (Onset HOBO data loggers, Cape Cod, Massachusetts, USA) were installed in each plot in three of the four replications 23 cm below the soil surface in 2011 and 5 cm below the soil surface in 2012. Sensors were set at different depths in 2011 and 2012 to determine differences in soil temperature caused by mulches at soil depths deeper in the soil profile for understanding crop root zone temperature exposure in 2011 and closer to the soil surface in 2012 to gain information pertinent to conditions encountered by weed seeds, microorganisms, and roots close to the surface. The data loggers recorded hourly soil temperature measurements for the duration of the growing season, from July 19 through September 16, 2011 and June 14 through September 10, 2012. Both the temperature
sensors and the soil moisture probe were inserted beneath the mulch materials so that measurements were taken at the same soil depth for all treatments.

Soil growing degree days (GDD) were calculated for each treatment to determine if mulch treatments led to more rapid crop growth that would enable earlier harvests. Soil GDD were calculated by averaging the daily maximum temperature and daily minimum temperature and subtracting the base temperature of 20°C from this value (see equation below). Cumulative soil GDD for the entire growing season were calculated for each treatment by summing the GDD accumulated for each day.

\[
\text{Soil GDD} = \left[ \frac{(\text{daily max} + \text{daily min})}{2} \right] - 20^\circ \text{C}
\]

In 2012, soil samples were taken at a depth of 20 cm using a soil corer on June 8, before mulches were applied and the field was planted. Three 51 cm³ cores were taken per plot and mixed together for a bulk sample from each plot. Samples were taken again at the end of the season using the same method on September 14, 2012. The samples were analyzed for total carbon and nitrogen (CLC labs, 325 Venture Drive, Westerville, Ohio).

The effect of the mulches on plant growth was assessed by taking plant volume measurements in 2011 and 2012 and SPAD meter readings in 2012. Plant volume was measured using a measuring tape placed at the soil surface to the extension of the top-most leaf to measure height and placed from one outside leaf to the opposite outside leaf to measure width on July 27 and September 2, 2011 and on July 12, 2012. SPAD meter readings were taken using the Minolta SPAD-502 Plus chlorophyll meter (Spectrum Technologies, Plainfield, IL, USA) in 2012 to estimate leaf chlorophyll content. Leaf chlorophyll content is correlated with nitrogen content (Loh et al. 2002). SPAD meter
readings were taken on July 17 and August 24, 2012 by taking an average of three readings each on a young leaf close to the meristem of the plant, a mid-aged leaf, and an older leaf near the base of the plant.

Weekly pest and disease presence were recorded from August 3 to August 31, 2011 and from July 17 to August 24, 2012. Pest presence was assessed by inspecting the three center plants in each plot and recording the presence/absence and abundance of cucumber beetles and squash bug eggs, nymphs, and adults. Disease incidence was determined by noting the number of plants that exhibited symptoms of bacterial wilt, yellow vine decline, or powdery mildew.

Initial weed density, percent cover, and biomass were taken six weeks after planting in 2011 on July 28 and four weeks after planting in 2012 on July 10. This was done by placing a 0.5 m quadrat between the end two plants at the South end of the 1.2 m by 9.1 m plot. Percent weed cover was determined and weeds were counted by species, cut at the soil surface, placed in paper bags by species, dried at 55°C and weighed. After initial weed counts were taken in 2011, weeds were suppressed throughout the plot areas using a weed whacker on July 28, and again on August 23, 2011. This was necessary so that experimental plant loss in plots could be minimized since plants were also suffering from severe insect pest and disease damage. Final weed counts and percent cover were taken by placing a 0.5 m quadrat at the north end of each plot on September 2, 2011. No final biomass measurements were taken since the weed biomass present was from regrowth due to weeds being cut on August 23. In 2012, it was not necessary to suppress weeds in the plots, and weed counts, percent cover, and biomass measurements were taken at pumpkin harvest on September 12. Pumpkins were harvested from all living
plants by hand using pruning loppers on September 9, 2011 and September 10, 2012. The number of marketable, rotted, and damaged fruits was recorded, as well as fruit weight per plot.

**Statistical analyses**

Data for 2011 and 2012 were analyzed separately due to a significant treatment by year interaction for the dependent variables: soil moisture and temperature, yield, and weed response parameters. All data were subject to analysis of variance (ANOVA) using the PROC MIXED procedure in SAS for a randomized complete block design with blocks as a random effect and treatment as a fixed effect for both years of the experiments (Statistical Analysis System version 9.3 for Windows™; SAS Institute, Cary, NC). Plot within sampling date was designated as a random effect and plot was also designated as the subject on which repeated measures were taken for soil temperature and moisture. Unstructured covariance was specified in the model. Differences among least squares treatment means were determined using pairwise t-tests implemented by the PDIFF option with a comparisonwise error rate of alpha = 0.05 (Littell et al. 2006). Pest, disease, and weed response data were transformed using either a box cox transformation under the PROC TRANSREG procedure or a square root transformation for analysis and means separation of non-normally distributed data. Means were back-transformed for presentation in tables and figures. The transformations used for the each dataset are presented in Appendix C.

**3.5 Results**

**Soil Moisture, Temperature, and C:N ratio.** The weather encountered during 2011 and 2012 was dramatically different. In 2011 there was a wet spring with precipitation
totaling 30 cm from June through August. Total precipitation during the same period in 2012 was only 16 cm. In comparison, the 30-year average for this time period is 33 cm (Fig. 3.1). During the 2011 field season, no irrigation was needed, however in 2012, plots were irrigated every three days during the early part of the season to avoid water-stressing the plants.

Soil moisture differed between treatments, but also differed throughout the course of a season and between years. In 2011 and 2012 there were significant date by treatment interactions (2011: $P < 0.001$, 2012: $P < 0.0001$). In the wet summer of 2011, soil moisture in newspaper plots was initially greater than in the other treatments (Fig. 3.2). When a dry period occurred later in August, newspaper mulch still had higher soil moisture levels, but the difference between treatments was not as extreme. Plastic mulch had the lowest volumetric soil water content in 2011. Similarly, during the drier summer of 2012, plastic mulch had the lowest volumetric soil water content throughout the entire season; the bare soil treatment had variable soil water content that fluctuated according to rain events; and newspaper, woodchip, and NP+grass grass mulches retained higher soil moisture levels throughout the season with less fluctuation.

Average ambient air temperature was roughly the same during both years of study, however, there was a spike in temperatures in early September of 2011 (Fig. 3.3). Soil average, minimum, and maximum temperatures differed between treatments in 2011 and 2012 (Table 3.1). Bare soil had the lowest average soil temperature in both 2011 and 2012. In 2011, plastic, woodchips and newspaper resulted in the highest average soil temperatures and in 2012 plastic, woodchips and NP+grass resulted in the highest average soil temperatures (2011: $P < 0.0001$, 2012: $P < 0.005$). In 2011, woodchip mulch
generated the lowest minimum soil temperatures compared to all other treatments and in 2012 woodchips, newspaper and NP+grass generated the lowest minimum soil temperatures (2011: P < 0.0001, 2012: P < 0.005). Woodchip mulch plots had the highest maximum soil temperatures in 2011, while in 2012, woodchip mulch and NP+grass mulch plots had the highest maximum soil temperatures compared to the other treatments (P < 0.0001, 2012: P < 0.0001). This effect of creating temperature extremes in soil directly beneath mulch materials led to woodchips and NP+grass plots having the greatest fluctuation in soil temperatures in both 2011 and 2012 (2011: P < 0.0001, 2012: P < 0.0001) (Table 3.1). Soil temperature fluctuation was calculated by subtracting the daily minimum temperature from the daily maximum temperature.

Cumulative soil growing degree days (GDD) were calculated for 2012, but not for 2011 due to missing data. NP+grass accumulated the most soil GDD, followed by woodchip mulch, with separation between treatments occurring on August 20 or 8 weeks after planting (P < 0.0001) (Table 3.2). There was no difference in cumulative soil GDD between plastic and newspaper plots that generated the fewest soil GDD (Fig. 3.4).

Soil carbon to nitrogen ratio (C:N), measured in 2012 only, did not change after mulches had been in place for four months (Table 3.3). No nitrogen immobilization occurred in any of the treatments since none of the C:N ratios of soil collected from treatment plots increased after mulches had been in place for the duration of a single season.

**Plant Growth.** In 2011, plots mulched with NP+grass mulch produced larger plants than other treatments (P = 0.05) (Table 3.4). In 2012, there were no differences in plant volume among mulch treatments but, plants in NP+grass, woodchip, and newspaper plots
had higher leaf chlorophyll content than plants grown in bare soil plots (P = 0.05) indicating higher nitrogen acquisition in those plots (Table 3.4).

Pest and Disease Presence. There were no differences in the total number of Chrysomelidae, which included striped and spotted cucumber beetles and western corn rootworm adults, among mulch treatments in 2011 or 2012 (Table 3.5). Plastic plots harbored more stripped cucumber beetles (*Acalymma vittatum*) than NP+grass, woodchip, bare and plots in 2011 (P < 0.05), but in 2012, there were no differences in the number of *A. vittatum* among treatments (Table 3.5).

There were differences in total squash bug number (*Anasa tristis*) between treatments in 2011 and 2012 (Table 3.6). In 2011, total *A. tristis* presence was higher in plastic, newspaper, and NP+grass plots than in bare plots (P < 0.01). Total *A. tristis* presence was higher in NP+grass plots than all other treatments in 2012 (P < 0.0001). In 2011, there were more *A. tristis* nymphs in plastic, woodchips, and NP+grass plots than in bare soil plots (P < 0.05). However in 2012, there were more *A. tristis* eggs found within NP+grass plots than in all other treatments (P < 0.0001).

Due to high disease incidence in 2011, disease symptoms due to bacterial wilt, yellow vine decline, and powdery mildew could not be differentiated and data were not analyzed. Disease incidence differed between treatments during the 2012 growing season (Table 3.7). Newspaper and NP+grass plots had higher percentages of bacterial wilt, a disease vectored by cucumber beetles, than bare and plastic plots (P = 0.05). However, plastic and woodchip plots had higher percentages of cucurbit yellow vine decline, a disease transmitted by squash bugs, than bare plots (P < 0.05). During the later portion of
the growing season bare and woodchip plots had higher percentages of powdery mildew compared to plastic, newspaper and NP+grass plots (P < 0.05).

**Weed Response.** The most abundant weed in 2011 was Common lambsquarters (*Chenopodium album* L.), which accounted for 18% of total biomass in bare soil, weedy-check plots at six weeks after planting (WAP). Redroot pigweed (*Amaranthus retroflexus* L.) was the most abundant weed in 2012 and composed 18% of total biomass in bare plots averaged across both weed harvest dates. In 2011, *C. album* density (P < 0.0001), percent cover (P < 0.0001), and biomass (P < 0.0001) were lower in plastic, woodchip, newspaper, and NP+grass than in bare soil plots at six WAP (Table 3.8). *Chenopodium album* density was lower in all mulch treatments than bare soil at 12 WAP (P < 0.005) but there were no differences in *C. album* percent cover among mulches.

Total weed biomass differed between treatments and between weed harvest dates in 2011 (Table 3.8). At six WAP, plastic mulch resulted in 100% control of weed density and biomass. Woodchip and newspaper resulted in 9.8 and 3.4 g of weed biomass per m² respectively, representing a 93% and 97% reduction in weed biomass compared to bare soil and performing better than NP+grass, which resulted in 33.6 g per m², representing only a 74% reduction (P < 0.0001). However at 12 WAP, woodchips, newspaper, and NP+grass plots did not differ in weed density or weed percent cover and newspaper plots provided control comparable to black plastic resulting in 9.7 weeds per m² and 29.7% coverage by weeds per m², representing a 90% reduction in weed density and a 77% reduction in percent cover (P < 0.001). Due to considerable weed pressure in 2011, black plastic did not achieve 100% control and resulted in a percent cover value of 14.2% per m², which represents a reduction in weed cover of only 89% compared to bare soil.
In 2012, weed pressure was considerably lower than in 2011 (Table 3.9). *Amaranthus retroflexus* density (P < 0.0001), percent cover (P < 0.0001), and biomass (P < 0.0001) was lower in plastic, woodchip, newspaper, and NP+grass plots compared to bare soil at four and 14 WAP (density: P < 0.005, percent cover: P < 0.01, biomass: P < 0.01). Plastic, newspaper, and NP+grass achieved 100% control of *A. retroflexus* and woodchip mulch resulted in *A. retroflexus* biomass of 0.3 g per m$^2$, which represents a 97% reduction in biomass compared to bare soil at four WAP. At 14 WAP, woodchip, newspaper, and NP+grass resulted in 1.3, 1.3, and 0.2 g of *A. retroflexus* per m$^2$ respectively, each achieving greater than 99% control of *A. retroflexus*, with plastic maintaining 100% efficacy. Black plastic provided 100% control of total weed biomass at 4 WAP. Newspaper resulted in 0.1 g of weed biomass per m$^2$ and NP+grass resulted in 0 g of weed biomass per m$^2$, representing control that did not differ from black plastic. Woodchips did not perform as well as the other mulch treatments, resulting in 1 g of weed biomass per m$^2$, but still reduced total weed biomass by 99% compared to bare soil (P < 0.0001). At 14 WAP, newspaper, NP+grass, and woodchips did not differ from black plastic, all providing greater than 99% control of total weed biomass compared to that of bare soil plots (P < 0.01).

**Pumpkin Yield.** There were no differences in average weight per pumpkin, total pumpkin number, number of marketable pumpkins, or marketable pumpkin weight among treatments in 2011 (Table 3.10). Due to wet weather conditions and warm temperatures at the end of the 2011 season (Figs. 3.1 and 3.3), many pumpkins rotted before harvest and were not harvested, so for this reason total fresh weights including rotten pumpkins were not recorded. Also, the lack of difference in pumpkin number and weight between
treatments may be due to low pumpkin survivorship because of a combination of intense weed pressure and high incidence of pest and disease damage.

During the 2012 field season, there were differences in the number of total and marketable pumpkins (P < 0.05), and in the fresh weight of total (P < 0.01) and marketable pumpkins (P < 0.05) among treatments with plants grown in plastic, newspaper, and NP+grass plots producing more fruit than bare plots (Table 3.10). However, there were no differences among treatments in average weight per pumpkin.

3.4 Discussion

Particulate mulch materials, woodchips, newspaper, and NP+grass retained higher soil moisture levels than plastic mulch or bare soil in 2012, and newspaper conserved soil moisture better than all other treatments in 2011. Black, polyethylene plastic is an impervious material with no gaps often making it 100% effective in suppressing weeds (Cirujeda et al. 2012). This impervious property of black plastic also makes the material impervious to water, which can conserve water if drip irrigation is used beneath the material by creating a vapor barrier. However, it also prevents water infiltration from above and results in increased water runoff. Rice et al. (2001) found that the use of black plastic in tomato resulted in 2-4 times more water runoff. Particulate mulches allow for percolation of rain water to occur and can provide additional organic matter, which can increase the water holding capacity of soil (Mulumba and Lal 2008; Saroa and Lal 2003). Soil water retention is increased with particulate mulches because they serve as a vapor barrier to moisture loss by evaporation, while allowing for water infiltration from above and decreasing water runoff. Newspaper has a relatively high water holding capacity.
compared to other materials (Airaksinen et al. 2001), which may be why plots mulched with shredded newspaper retained more soil moisture than other treatments in 2011.

All mulches tested resulted in higher average soil temperatures compared to bare soil in 2011, but newspaper mulch had the lowest average soil temperature of all the mulch materials and did not differ from bare soil in 2012. Mulch effects on soil temperature differ depending on their composition and optical properties, such as color (Ham et al. 1993). Newspaper, which is light in color, reflects rather than absorbs thermal radiation causing soil beneath newspaper mulch to remain cooler. This finding agrees with previous reports of newspaper mulch resulting in lower soil temperatures compared to other mulch materials (Grassbaugh et al. 2004). Woodchip mulch and NP+grass mulch tended to have the greatest fluctuations in soil temperature, but also resulted in the highest number of soil GDD accumulated during the growing season. Previous work indicated that organic mulches decrease maximum soil temperatures while increasing minimum soil temperature resulting in less soil temperature fluctuation (Teasdale and Mohler 1993), which contradicts these findings. Greater soil temperature fluctuation associated with woodchip and NP+grass mulch may be due to increased soil moisture beneath these mulches. Because of the specific heat of water, the thermal conductivity of wet soil is greater than that of dry soil (Collis-George 1959), so mulches having higher soil moisture may have reached more extreme temperatures. However, if this were the case, newspaper plots would be expected to have had the greatest soil temperature fluctuation since newspaper retained higher soil moisture levels.

Another explanation of greater soil temperature fluctuation and rapid GDD accumulation in woodchip and NP+grass plots is increased microbial activity due to the
addition of nutrients and organic matter from the degradation of mulch components. Decomposing plant material in combination with adequate soil moisture and gas exchange providing oxygen supplies all the elements necessary for soil microbes to thrive. Fresh grass clippings release approximately 55% of their nitrogen in the first four months of decomposition (Fang et al. 2007) and woodchips decompose by roughly 32% after a year adding moderate amounts of calcium, magnesium, nitrogen, phosphorus, and potassium (Duryea et al. 1999). The addition of nutrients and organic matter by the degradation of grass clippings or woodchips could lead to increased activity by microbes which emit heat when active (MacGregor et al. 1981) and result in higher soil temperatures plus more rapid soil GDD accumulation. *Cucurbita pepo* is a warm season crop that benefits from an increased quality and duration of the growing season which results in increased yields and faster maturity (Swiader et al. 1992). There is a lag in crop growth until approximately 300 GDD have been accumulated with crop growth increasing in a linear fashion above 300 GDD (NeSmith 1997). Faster accumulation of GDD may lead to earlier harvests of pumpkin grown in NP+grass mulch.

There was no effect of the mulches on soil carbon and nitrogen, which contradicts previous work investigating the effects of newspaper and woodchips on soil fertility (Glenn et al. 2000; Craig and Cole 1997; Tahboub and Lindemann 2007). When materials having a high C:N ratio, such as newspaper or woodchips, are added to soil, the excess soil carbon leads to microorganisms using nitrogen from the soil to metabolize the carbon and compete with plants for the uptake of inorganic N (Tahboub and Lindemann 2007). The lack of effect on soil C:N by the mulches studied may be due to the fact that the mulches were not incorporated into the soil or left long enough on top of the soil.
surface to degrade sufficiently and influence soil C:N. However, this somewhat contradicts the hypothesis that greater soil temperature fluctuation occurred beneath woodchip and NP+grass mulch due to mulch component decomposition and increased microbial activity.

Weed suppression by mulches differed somewhat between years, but in general, all of the mulches tested provided greater than a 74% reduction in weed biomass compared to bare soil. Newspaper and NP+grass mulches offered weed suppression comparable to that of black plastic during the 2012 season. However, newspaper and woodchip mulches performed better than NP+grass mulch in 2011. In 2011, all three treatments, woodchips, newspaper, and NP+grass failed to provide weed control comparable to black plastic, with newspaper performing the best out of the three, reducing weed biomass by 97% during the critical period for weed control. Overall, the data support the hypothesis that shredded newspaper mulch offers weed suppression comparable to that of black plastic, although it may not be 100% effective in all conditions. However, it should be noted that during 2011, when weed pressure was considerably high, black plastic failed to control 100% of weeds as well.

Wet conditions and higher temperatures may have caused more rapid degradation of grass clippings in the NP+grass mulch during 2011. Grass clippings appeared to degrade quickly, and this may have left gaps within the NP+grass mulch that allowed weeds to emerge. Additions of nitrogen which may have occurred in NP+grass plots, has been shown to increase dark germination of *A. retroflexus*, which may also explain higher weed emergence in NP+grass mulch (Gallagher and Cardina 1998). I would expect that the particulate mulches tested would be most effective at controlling small-seeded annual
species (Teasdale and Mohler 2000). The high temperature fluctuations found in woodchip and NP+grass mulches may create conditions appropriate for breaking dormancy in many weed species, especially perennial species, which could lower their effectiveness for weed control (Bostock 1978).

Several characteristics could explain the effectiveness of shredded newspaper for weed control. The matrix of long, tangled strips adds to the tensile strength of shredded newspaper mulch, similar to how non-woven fabrics are held together (Xiang and Kuznetsov 2008). This tangled matrix of paper strips also presents a maze that may be difficult for an emerging weed seedling to navigate through. Through exposure to natural wetting and drying during rain events followed by dry periods shredded newspaper mulch forms a ‘crust’ on its upper surface. This crust may present a barrier with even greater tensile strength that further precludes weed emergence. However, this mulch characteristic is purely anecdotal and should be investigated further. Additionally, the effect of lower soil temperatures and moist soil conditions beneath shredded newspaper mulch could result in higher seed dormancy of buried weed seeds (Schafer and Chilcote 1970). One or a combination of these characteristics of shredded newspaper mulch may be responsible for its weed suppressive ability.

Plots with NP+grass mulch produced plants greater in size and with higher leaf chlorophyll content than plants grown on bare soil, which supports my original hypothesis that the addition of nitrogen from the grass clippings would result in greater plant growth than in other mulch treatments. All mulch treatments resulted in higher pumpkin yield than bare soil, but only plastic, newspaper, and NP+grass mulch treatments resulted in higher numbers of marketable fruits than bare soil. Mulches have
the ability to prevent soil contact with pumpkin fruits reducing attack by soil-borne fungi and resulting in more disease-free, salable pumpkins (Wyenandt et al. 2008). Mulches can also keep fields free of mud during inclement fall weather when there is a lot of foot traffic, such as in pick-your-own pumpkin operations, so that customers may have a more enjoyable experience (Wyenandt et al. 2008).

One challenge with using NP+grass mulch for *C. pepo* production may be increased pest and disease pressure due to *A. tristis*. In both years of study, *A. tristis* numbers were higher in NP+grass plots than bare soil plots. Previous work investigating *A. tristis* population dynamics in *C. pepo* systems where mulch is used had similar results, where mulch, regardless of type, harbored higher *A. tristis* populations than bare soil (Cartwright et al. 1990). Cranshaw et al. (2001) found that straw and plastic mulches resulted in increased damage by *A. tristis*. However, pest incidence was not so high in 2012 that it interfered with crop yield in NP+grass plots, which yielded a greater number of both total and marketable fruits. Also, higher numbers of *A. tristis* in NP+grass plots did not translate the highest incidences of yellow vine decline, the disease vectored by *A. tristis*, in 2012. *Anasa tristis* may prefer to live and breed in ground covered by mulch, particularly NP+grass mulch, but being a mobile organism, it moves about host plants within a field regardless of mulch type. This may explain why higher pest abundance did not necessarily predict greater disease incidence of those diseases vectored by the pests present.

The combination of shredded newspaper and grass clippings had a positive overall effect on crop performance through increased soil moisture conservation, greater soil GDD accumulation, improved plant growth and greater yields in pumpkin. Several
studies have demonstrated improved crop performance using shredded newspaper mulch (Grassbaugh et al. 2004; Pellett and Heleba 1995; Sanchez et al. 2008). Mulching with grass clippings also has positive effects on soil nutrient levels, which improves crop performance (Fang et al. 2007). However, the combination of these two mulch materials had not been tested previously. Shredded newspaper when combined with grass clippings demonstrated the positive impacts on crop performance that shredded newspaper and grass clippings have previously demonstrated separately.

The soil water conservation properties of newspaper and NP+grass mulch are of particular importance for urban agriculture. Conserving soil moisture around crop plants is beneficial for growth and fruit production and a cost-effective management practice in general. Decreasing the need for irrigation is especially important since agriculture consumes roughly 70% of the world’s fresh water supply (Pimentel et al. 2004). Water conservation could make the difference between having an adequate rather than an insufficient harvest in urban areas where irrigation may not be available. Furthermore, the chlorine and fluoride present in most city-treated water in the United States are some of the most phytotoxic of all common water pollutants and restrict the plant growth of many species including some crop species (Weinstein and Alscher-Herman 1982), so many urban growers may choose not to irrigate if their only option is city-treated water. Shredded newspaper and NP+grass mulches may be especially useful for small-scale urban production since they utilizes highly abundant municipal waste materials and have a positive impact on the performance of a major vegetable crop, Cucurbita pepo.

Further research is needed to determine the impacts of shredded newspaper mulch and grass clippings on long-term soil fertility, which lay outside of the scope of these
experiments. Challenges may exist in dealing with the incorporation of paper mulch into the soil. This practice may have a negative effect on soil carbon and nitrogen balance. No N immobilization was found during this study, but this may be because shredded newspaper mulch was not incorporated into the soil. Instead the mulches were left in place on the soil surface as an alternative to tillage. Comparing management strategies where mulch is incorporated into the soil versus a no-till approach to see mulch effects on soil fertility may be beneficial. The cost-effectiveness of using shredded newspaper mulch also needs to be assessed. In many areas waste newspaper and grass clippings can be obtained easily for almost no cost. However, shredding the paper may add cost and labor for farmers attempting to create this mulch. The dimension of the paper shreds is important for achieving a high degree of hydroentanglement, which creates the woven mat of fibers desired (see Appendix A). Achieving proper paper shred dimension for the production of shredded newspaper mulch and the ease of this process remains to be investigated fully.

There may also be other ways of arranging mulch materials to ease application. For this study grass clippings were mixed in with the shredded newspaper and wetted prior to application, but perhaps different effects would result from a layered approach where grass clippings are applied first with a layer of shredded newspaper on top of them. Many possibilities exist with various particulate mulch materials and their method of application that merit further study.

In conclusion, mulches consisting of municipal waste materials have positive impacts on weed suppression and crop performance, making them highly suitable for sustainable production of fruit and vegetable crops within urban environments.
Production techniques for growing fruits and vegetables are adaptable to the small scale that the urban environment provides. These crops also tend to be more perishable, so growing them closer to where they are to be consumed is sensible and less costly (Mendes 2008). Moreover, these crops provide a source of nutrients essential for human health that may be unavailable to many people in some urban locations (Steffan-Dewenter et al. 2005). More management practices should be investigated for their potential application to increase the sustainability of food systems within urban environments.

3.5 References


### 3.6 Tables and Figures

Table 3.1 Comparison of least squares means from a linear mixed model of the effects of mulch type on soil temperature in 2011 and 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Year</th>
<th>Mulch Type</th>
<th>Average Soil Temperature (°C)</th>
<th>Minimum Soil Temperature (°C)</th>
<th>Maximum Soil Temperature (°C)</th>
<th>Soil Temperature Fluctuation (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Bare</td>
<td>23.5 c</td>
<td>17.7 b</td>
<td>30.3 c</td>
<td>12.6 d</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>23.9 a</td>
<td>17.9 a</td>
<td>30.9 b</td>
<td>13.0 bc</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>23.8 ab</td>
<td>17.5 c</td>
<td>31.3 a</td>
<td>13.8 a</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>23.8 ab</td>
<td>17.9 a</td>
<td>30.7 b</td>
<td>12.8 cd</td>
</tr>
<tr>
<td></td>
<td>NP+grass</td>
<td>23.7 b</td>
<td>17.7 b</td>
<td>30.9 b</td>
<td>13.2 b</td>
</tr>
<tr>
<td>2012</td>
<td>Bare</td>
<td>23.7 b</td>
<td>17.1 ab</td>
<td>31.2 b</td>
<td>14.1 b</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>28.8 a</td>
<td>17.2 a</td>
<td>31.2 b</td>
<td>14.0 b</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>23.9 a</td>
<td>17.1 b</td>
<td>31.6 a</td>
<td>14.5 a</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>23.7 b</td>
<td>17.1 b</td>
<td>31.3 b</td>
<td>14.2 b</td>
</tr>
<tr>
<td></td>
<td>NP+grass</td>
<td>28.8 a</td>
<td>16.9 b</td>
<td>31.7 a</td>
<td>14.7 a</td>
</tr>
</tbody>
</table>

*Least squares means within a year and column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of $\alpha = 0.05$. 

**Note:** The text and tables are presented as they appear in the document, without alteration or interpretation.
Table 3.2 Comparison of least squares means from a linear mixed model of the effects of mulch type on soil growing degree days (GDD) in 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Mulch</th>
<th>Soil GDD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 WAP&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Bare</td>
<td>136</td>
</tr>
<tr>
<td>Plastic</td>
<td>132</td>
</tr>
<tr>
<td>Woodchips</td>
<td>137</td>
</tr>
<tr>
<td>Newspaper</td>
<td>132</td>
</tr>
<tr>
<td>NP+grass</td>
<td>138</td>
</tr>
</tbody>
</table>

<sup>a</sup> Columns lacking letters indicate no significant treatment effect.

<sup>b</sup> Least squares means within a column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of $\alpha = 0.05$. 


Table 3.3 Comparison of least squares means from a linear mixed model of the effects of mulch type on soil C:N in 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Mulch Type</th>
<th>Initial C:N&lt;sup&gt;a&lt;/sup&gt;</th>
<th>Final C:N&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Average Difference&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>19:1</td>
<td>18:1</td>
<td>-1.3</td>
</tr>
<tr>
<td>Plastic</td>
<td>19:1</td>
<td>17:1</td>
<td>-2.0</td>
</tr>
<tr>
<td>Woodchips</td>
<td>20:1</td>
<td>17:1</td>
<td>-2.3</td>
</tr>
<tr>
<td>Newspaper</td>
<td>19:1</td>
<td>18:1</td>
<td>-1.0</td>
</tr>
<tr>
<td>NP+Grass</td>
<td>19:1</td>
<td>18:1</td>
<td>-0.3</td>
</tr>
</tbody>
</table>

<sup>a</sup> Initial C:N measurements were taken on June 8, 2012 three days before planting.

<sup>b</sup> Final C:N measurements were taken on September 14, 2012 one month after pumpkin harvest and approximately four months after mulch application.

<sup>c</sup> Columns lacking letters indicate no significant treatment effect according to pairwise t-tests with a comparisonwise error rate of alpha = 0.05.
Table 3.4 Comparison of least squares means from a linear mixed model of the effects of mulch type on pumpkin plant volume in 2011 and 2012 and average SPAD value depicting leaf tissue chlorophyll content in 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Mulch Type</th>
<th>Plant Volume 2011 (m$^3$)$^a$</th>
<th>Average Plant Volume (m$^3$)$^{bc}$</th>
<th>SPAD$^d$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6 WAP</td>
<td>11 WAP</td>
<td>2011</td>
</tr>
<tr>
<td>Bare</td>
<td>2.2</td>
<td>4.7</td>
<td>3.5</td>
</tr>
<tr>
<td>Plastic</td>
<td>3.0</td>
<td>6.4</td>
<td>4.6</td>
</tr>
<tr>
<td>Woodchips</td>
<td>2.2</td>
<td>6.5</td>
<td>4.4</td>
</tr>
<tr>
<td>Newspaper</td>
<td>2.1</td>
<td>5.9</td>
<td>4.0</td>
</tr>
<tr>
<td>NP+grass</td>
<td>4.5</td>
<td>8.8</td>
<td>6.7</td>
</tr>
</tbody>
</table>

$^a$ An early and late plant volume was measured in 2011, but not in 2012 due to plants becoming too large and intertwined to measure at maturity.

$^b$ Average plant volume for 2011 represents the least squares mean of early and late plant volumes, but only the least square means of the early plant volume for 2012 measured 4 WAP.

$^c$ Columns lacking letters indicate no significant treatment effect.

$^d$ Least squares means within a column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of $\alpha = 0.05$. 

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Table 3.5 Comparison of least squares means from a linear mixed model of the effects of mulch type on Chrysomelidae presence in 2011 and 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Year</th>
<th>Mulch Type</th>
<th>Chrysomelidae (no.)</th>
<th>A. vittatum (no.)</th>
<th>D. undecimpunctata (no.)</th>
<th>D. virgifera (no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Bare</td>
<td>1.7(^{b})</td>
<td>0.7(^{b})(^{c})</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>3.0</td>
<td>1.9(^{a})</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>1.6</td>
<td>0.7(^{b})</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>2.6</td>
<td>1.5(^{ab})</td>
<td>0.1</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>NP+ Grass</td>
<td>1.9</td>
<td>0.8(^{b})</td>
<td>0.1</td>
<td>0.4</td>
</tr>
<tr>
<td>2012</td>
<td>Bare</td>
<td>1.9</td>
<td>1.0</td>
<td>0.4</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>1.9</td>
<td>1.3</td>
<td>0.4</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>1.7</td>
<td>0.8</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>2.2</td>
<td>1.1</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>NP+ Grass</td>
<td>1.8</td>
<td>0.9</td>
<td>0.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>

\(^{a}\) Average number of striped cucumber beetle (*Acalymma vittatum*), spotted cucumber beetle (*Diabrotica undecimpunctata*), and/or western corn root worm (*Diabrotica virgifera virgifera*) all belonging to the family Chrysomelidae, found on the three plants per plot surveyed over a 5 to 6 week period in 2011 and 2012.

\(^{b}\) Columns lacking letters indicate no significant treatment effect.

\(^{c}\) Least squares means within a year and column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of \(\alpha = 0.05\).
Table 3.6 Comparison of least squares means from a linear mixed model of the effects of mulch type on squash bug (*Anasa tristis*) presence in 2011 and 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Year</th>
<th>Mulch Type</th>
<th>Total <em>Anasa tristis</em> (no.)$^a$</th>
<th><em>A. tristis</em> Eggs (no.)</th>
<th><em>A. tristis</em> Nymphs (no.)</th>
<th><em>A. tristis</em> Adults (no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Bare</td>
<td>3.5 c</td>
<td>0.2$^c$</td>
<td>2.3 c</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>5.1 a</td>
<td>0.9</td>
<td>2.9 a</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>4.3 bc</td>
<td>0.8</td>
<td>2.6 abc</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>4.4 ab</td>
<td>0.9</td>
<td>2.5 bc</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>NP+ Grass</td>
<td>4.6 ab</td>
<td>0.5</td>
<td>2.8 ab</td>
<td>0.1</td>
</tr>
<tr>
<td>2012</td>
<td>Bare</td>
<td>0.1 c</td>
<td>0.1 c</td>
<td>0.0 c</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>1.2 b</td>
<td>1.0 b</td>
<td>0.1 bc</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>1.3 b</td>
<td>1.0 b</td>
<td>0.3 ab</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>1.4 b</td>
<td>1.1 b</td>
<td>0.4 ab</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>NP+ Grass</td>
<td>2.3 a</td>
<td>1.8 a</td>
<td>0.5 a</td>
<td>0.1</td>
</tr>
</tbody>
</table>

$^a$ Average number of total *A. tristis* and *A. tristis* eggs, nymphs, and eggs found on the three plants per plot surveyed over a 5 to 6 week period in 2011 and 2012.

$^b$ Least squares means within a year and column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of $\alpha = 0.05$.

$^c$ Columns lacking letters indicate no significant treatment effect.
Table 3.7 Comparison of least squares means from a linear mixed model of the effects of mulch type on incidence of disease in 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Mulch Type</th>
<th>Bacterial Wilt (%) (^{ab})</th>
<th>Yellow Vine Decline (%)</th>
<th>Powdery Mildew (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>1.4  b</td>
<td>3.7  b</td>
<td>15.4  a</td>
</tr>
<tr>
<td>Plastic</td>
<td>2.7  b</td>
<td>11.0 a</td>
<td>5.3  b</td>
</tr>
<tr>
<td>Woodchips</td>
<td>3.5  ab</td>
<td>15.6 a</td>
<td>15.0 a</td>
</tr>
<tr>
<td>Newspaper</td>
<td>7.2  a</td>
<td>9.4  ab</td>
<td>4.5  b</td>
</tr>
<tr>
<td>NP+Grass</td>
<td>5.9  a</td>
<td>8.8  ab</td>
<td>5.5  b</td>
</tr>
</tbody>
</table>

\(^{a}\) Bacterial wilt, yellow vine decline, and powdery mildew percent data were square root transformed for analysis and means separation; means presented are backtransformed.

\(^{b}\) Least squares means within a column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of \(\alpha = 0.05\).
Table 3.8 Common lambsquarters (CHEAL) and total weed density and dry biomass per 1 m² associated with mulch treatments at 6 weeks after planting (WAP) and at harvest 12 WAP in 2011. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Weed</th>
<th>Mulch Type</th>
<th>6 WAP</th>
<th>12 WAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>no. per m²</td>
<td>% cover per m²</td>
</tr>
<tr>
<td>CHEAL</td>
<td>Bare</td>
<td>52.6 a</td>
<td>24.3 a</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>0.0 b</td>
<td>0.00 b</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>0.4 b</td>
<td>0.3 b</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>0.0 b</td>
<td>0.0 b</td>
</tr>
<tr>
<td></td>
<td>NP+Grass</td>
<td>0.3 b</td>
<td>0.3 b</td>
</tr>
<tr>
<td>Total</td>
<td>Bare</td>
<td>207.5 a</td>
<td>143.7 a</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>0.0 c</td>
<td>0.0 c</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>17.9 b</td>
<td>17.3 b</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>18.0 b</td>
<td>24.9 b</td>
</tr>
<tr>
<td></td>
<td>NP+Grass</td>
<td>20.2 b</td>
<td>42.8 b</td>
</tr>
</tbody>
</table>

*a* Least squares means within a weed type and main effect column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of alpha = 0.05.

*b* Columns lacking letters indicate no significant treatment effect.
Table 3.9 Red root pigweed (AMARE) and total weed density per 1 m² associated with mulch treatments at 4 weeks after planting (WAP) and at harvest 14 WAP in 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Weed</th>
<th>Mulch Type</th>
<th>4 WAP</th>
<th>14 WAP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>no. per m²</td>
<td>% cover per m²</td>
<td>g per m²</td>
</tr>
<tr>
<td>AMARE</td>
<td>Bare</td>
<td>8.0 a</td>
<td>54.4 a</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>0.0 b</td>
<td>0.0 b</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>0.3 b</td>
<td>0.5 b</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>0.0 b</td>
<td>0.0 b</td>
</tr>
<tr>
<td></td>
<td>NP+Grass</td>
<td>0.0 b</td>
<td>0.0 b</td>
</tr>
<tr>
<td>Total</td>
<td>Bare</td>
<td>64.8 a</td>
<td>164.7 a</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>0.0 c</td>
<td>0.0 c</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>1.5 b</td>
<td>3.7 b</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>0.3 c</td>
<td>0.6 c</td>
</tr>
<tr>
<td></td>
<td>NP+Grass</td>
<td>0.0 c</td>
<td>0.0 c</td>
</tr>
</tbody>
</table>

*Least squares means within a weed type and column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of \( \alpha = 0.05 \).
Table 3.10 Comparison of least squares means from a linear mixed model of the effects of mulch type on pumpkin yield in 2011 and 2012. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass).

<table>
<thead>
<tr>
<th>Year (g/plot)</th>
<th>Mulch Type</th>
<th>Fruit Weight (g/fruit)</th>
<th>Total Fruits (no/plot)</th>
<th>Total Marketable Fruit (no/plot)</th>
<th>Total Fruit Weight (g/plot)</th>
<th>Total Marketable Fruit Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>Bare</td>
<td>32.0(^a)</td>
<td>2.0</td>
<td>1.5</td>
<td>-</td>
<td>51.0</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>24.0</td>
<td>3.8</td>
<td>0.8</td>
<td>-</td>
<td>17.0</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>97.5</td>
<td>6.0</td>
<td>4.5</td>
<td>-</td>
<td>567.0</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>81.7</td>
<td>5.5</td>
<td>2.5</td>
<td>-</td>
<td>334.5</td>
</tr>
<tr>
<td></td>
<td>NP+Grass</td>
<td>86.2</td>
<td>5.3</td>
<td>3.3</td>
<td>-</td>
<td>351.5</td>
</tr>
<tr>
<td>2012</td>
<td>Bare</td>
<td>1670.8</td>
<td>12.8 (^a)(^b)</td>
<td>12.8 (^c)</td>
<td>21412 (^a)</td>
<td>21412 (^b)</td>
</tr>
<tr>
<td></td>
<td>Plastic</td>
<td>1913.9</td>
<td>20.3 (^b)</td>
<td>19.5 (^ab)</td>
<td>38636 (^b)</td>
<td>37037 (^a)</td>
</tr>
<tr>
<td></td>
<td>Woodchips</td>
<td>1754.9</td>
<td>18.3 (^b)</td>
<td>16.8 (^bc)</td>
<td>32565 (^b)</td>
<td>31127 (^ab)</td>
</tr>
<tr>
<td></td>
<td>Newspaper</td>
<td>1729.3</td>
<td>21.8 (^b)</td>
<td>21.0 (^ab)</td>
<td>37614 (^b)</td>
<td>36990 (^a)</td>
</tr>
<tr>
<td></td>
<td>NP+Grass</td>
<td>1803.0</td>
<td>22.5 (^b)</td>
<td>21.8 (^a)</td>
<td>40608 (^b)</td>
<td>39565 (^a)</td>
</tr>
</tbody>
</table>

\(^a\) Columns lacking letters indicate no significant treatment effect.

\(^b\) Least squares means within a year and column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of \(\alpha = 0.05\).
Figure 3.1 OARDC weather station data from Columbus, OH for dates corresponding to the 2011 and 2012 growing seasons. A: daily precipitation July through September 2011, B: daily precipitation June through September 2012.

Figure 3.2 Average volumetric soil water content where each line represents a different mulch treatment. Vertical bars represent ± SE. A: 2011 values during July through August, B: 2012 values during June through August.
Figure 3.3 OARDC weather station data from Columbus, OH for dates corresponding to the 2011 and 2012 growing seasons. A: daily maximum, minimum, and average air temperature July through September 2011, B: daily maximum, minimum, and average air temperature June through September 2012.

Figure 3.4 Cumulative soil growing degree days (GDD) accumulated by each treatment from planting to harvest.
All References


Rees, H.W., T.L. Chow, P.J. Loro, J. Lovoie, J.O. Monteith, A. Blaauw. 2002. Hay mulching to reduce runoff and soil loss under intensive potato production in


Figure A.1 Amount of newspaper lost after 40 seconds of wind exposure. Wind was generated using a fan placed on the floor along with the shredded paper treatments.

Methods: This experiment was performed in the Weed Ecology lab in Kottman Hall at The Ohio State University, Columbus, OH. Newspaper was cut into shreds of varying rectangularity (denoting the ratio of length to width) using a paper cutting board. The rectangularities tested were: 1.5 cm by 1.5 cm (r=1), 3.6 cm by 0.7 cm (r=5), 5 cm by 0.5 cm (r=10), 7 cm by 0.35 cm (r=20), and paper shredded using an office paper shredder producing shreds exactly 0.4 cm wide and approximately 6.25 cm long (“shredded”, r≈16). Each treatment was replicated three times. Between 10 and 13 g of paper shreds from each treatment were placed inside a cylinder made of aluminum flashing with open ends. The cylinder and shreds were placed on top of blotter paper on a mesh greenhouse.
bench. Water was applied to the paper shreds for two minutes at a pressure of 30 psi. After being jetted with water, the paper “cakes” were left to dry for one week before testing. The paper cakes were weighed using an analytical balance before and after being exposed to 40 seconds of wind from an industrial strength, heavy-duty air circulator (Patton, subsidiary of Jarden Corporation, Providence, RI, USA).
Appendix B: Pollen Data from 2012 Field Experiments

See Chapter 2, pages 58-60 for methods information.

Table B.1 Comparison of least squares means from a linear mixed model of the effects of mulch type on pollen quantity in the 2012 field experiment. Mulches included no mulch (bare), black plastic, woodchips, shredded newspaper, and shredded newspaper mixed with grass clippings (NP+grass) for the field experiment.

<table>
<thead>
<tr>
<th>Mulch Type</th>
<th>7/24/12&lt;sup&gt;a&lt;/sup&gt;</th>
<th>8/7/12</th>
<th>8/20/12&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare</td>
<td>30665&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>44150&lt;sup&gt;a&lt;/sup&gt;</td>
<td>25718</td>
</tr>
<tr>
<td>Plastic</td>
<td>24834&lt;sup&gt;b&lt;/sup&gt;</td>
<td>47814&lt;sup&gt;a&lt;/sup&gt;</td>
<td>21834</td>
</tr>
<tr>
<td>Woodchips</td>
<td>21113&lt;sup&gt;b&lt;/sup&gt;</td>
<td>51352&lt;sup&gt;a&lt;/sup&gt;</td>
<td>23938</td>
</tr>
<tr>
<td>Newspaper</td>
<td>40556&lt;sup&gt;a&lt;/sup&gt;</td>
<td>28795&lt;sup&gt;b&lt;/sup&gt;</td>
<td>20657</td>
</tr>
<tr>
<td>NP+grass</td>
<td>39508&lt;sup&gt;a&lt;/sup&gt;</td>
<td>25462&lt;sup&gt;b&lt;/sup&gt;</td>
<td>24917</td>
</tr>
</tbody>
</table>

<sup>a</sup> Least squares means within a column that are followed by the same lower case letter are not significantly different according to pairwise t-tests with a comparisonwise error rate of alpha = 0.05.

<sup>b</sup> Columns lacking letters indicate no significant treatment effect.
Appendix C: Data Transformations

Pest data transformations:

Refers to Chapter 3, Table 5
2011 Chrysomelidae presence data were $x^{0.1}$ transformed for analysis and means separation.
2011 *A. vittatum* presence data were $x^{-0.27}$ transformed for analysis and means separation.
2012 *A. vittatum* presence data were square root transformed for analysis and means separation.
2011 *D. undecimpunctata* presence data were $x^{-3}$ transformed for analysis and means separation.
2012 *D. undecimpunctata* presence data were square root transformed for analysis and means separation.
2011 *D. virgifera* presence data were $x^{-1.31}$ transformed for analysis and means separation.
2012 *D. virgifera* presence data were transformed for analysis and means separation.

Refers to Chapter 3, Table 5
2011 total *A. tristis* presence data were $x^{1.39}$ transformed for analysis and means separation.
2012 total *A. tristis* presence data were $x^{0.08}$ transformed for analysis and means separation.
2011 *A. tristis* egg presence data were $x^{0.92}$ transformed for analysis and means separation.
2012 *A. tristis* egg presence data were square root transformed for analysis and means separation.
2011 *A. tristis* nymph presence data were $x^{3}$ transformed for analysis and means separation.
2012 *A. tristis* nymph presence data were square root transformed for analysis and means separation.
2011 *A. tristis* adult presence data were $x^{-3}$ transformed for analysis and means separation.
2012 *A. tristis* adult presence data were square root transformed for analysis and means separation.
**Disease data transformations:**

*Refers to Chapter 3, Table 7*

2012 bacterial wilt, yellow vine decline, and powdery mildew symptom data were square root transformed for analysis and means separation.

**Weed data transformations:**

*Refers to Chapter 3, Table 8*

2011 *C. album* density data from 6 WAP were $x^{-0.89}$ transformed for analysis and means separation.
2011 *C. album* percent cover data from 6 WAP were $x^{-1.14}$ transformed for analysis and means separation.
2011 *C. album* biomass data from 6 WAP were $x^{-1.23}$ transformed for analysis and means separation.
2011 total weed density data from 6 WAP were $x^{0.04}$ transformed for analysis and means separation.
2011 total weed percent cover data from 6 WAP were $x^{0.17}$ transformed for analysis and means separation.
2011 total weed biomass data from 6 WAP were $x^{-0.05}$ transformed for analysis and means separation.
2011 *C. album* density data from 12 WAP were $x^{-0.54}$ transformed for analysis and means separation.
2011 *C. album* percent cover data from 12 WAP were $x^{-0.43}$ transformed for analysis and means separation.
2011 total weed density data from 12 WAP were $x^{0.16}$ transformed for analysis and means separation.
2011 total weed percent cover data from 12 WAP were $x^{0.51}$ transformed for analysis and means separation.

*Refers to Chapter 3, Table 9*

2012 *A. retroflexus* density data from 4 WAP were $x^{-1.43}$ transformed for analysis and means separation.
2012 *A. retroflexus* percent cover data from 4 WAP were $x^{-1}$ transformed for analysis and means separation.
2012 *A. retroflexus* biomass data from 4 WAP were $x^{-1.3}$ transformed for analysis and means separation.
2012 total weed density data from 4 WAP were $x^{-0.76}$ transformed for analysis and means separation.
2012 total weed percent cover data from 4 WAP were $x^{-0.49}$ transformed for analysis and means separation.
2012 total weed biomass data from 4 WAP were $x^{-0.86}$ transformed for analysis and means separation.
2012 *A. retroflexus* density data from 14 WAP were $x^{-1.27}$ transformed for analysis and means separation.
2012 *A. retroflexus* percent cover data from 14 WAP were $x^{-0.61}$ transformed for analysis and means separation.

2012 *A. retroflexus* biomass data from 14 WAP were $x^{-0.51}$ transformed for analysis and means separation.

2012 total weed density data from 14 WAP were $x^{-0.42}$ transformed for analysis and means separation.

2012 total weed percent cover data from 14 WAP were $x^{-0.25}$ transformed for analysis and means separation.

2012 total weed biomass data from 14 WAP were $x^{-0.32}$ transformed for analysis and means separation.