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Biopesticide Use In IPM For Low Desert Vegetable And Fruit Production

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BIOPESTICIDE USE IN IPM FOR LOW DESERT VEGETABLE AND FRUIT PRODUCTION

by

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Like most other agricultural areas, the low desert valleys of the southwestern United States experience issues with crop pests. Although the arid environment is not suitable for some pests, others thrive in microclimates that develop in each individual irrigated field. These crop pests whether they are insects or pathogens must be managed in a sustainable and environmentally friendly way. Throughout the past 50 to 60 years there has been an over-reliance on synthetic pesticides to manage these issues in agriculture. This over-reliance has allowed crop pests to develop resistance to many of these control products. Due to the development of resistance there has been a push for the use of more integrated management strategies and for products that fit better into these management programs. Biopesticides are currently being developed that can work both as alternatives to synthetic pesticides or in rotation with them to provide an additional control tactic in Integrated Pest Management (IPM) programs.

The following document was written and submitted after participating in a three-month internship at Research Designed for Agriculture (RD4AG) in Yuma, Arizona. Under the supervision of Steve and Lee West my internship's primary objective was to coordinate and conduct contracted agricultural industry research trials. A brief description of farming practices for the Yuma Valley area of southwestern Arizona is

provided that highlights IPM with the use of biopesticides. The document has a special emphasis on the management of Western Flower Thrips (*Frankliniella occidentalis* (Pergande)) as a pest in tomatoes (*Solanum lycopersicum* L.) and bell peppers (*Capsicum annuum* L.). The document also provides details on powdery mildew (*Sphaerotheca fuliginea* (Schlechtend: Fr.) Pollacci, *Leveillula taurica* (Lév) G. Arnaud) as a disease on cantaloupe (*Cucumis melo* L.) and bell peppers in the low desert

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CHAPTER 1

LOW DESERT CROP PRODUCTION IN ARIZONA

During a required internship for the University of Nebraska-Lincoln Doctor of Plant Health program, I served as a Biological Research Intern for Research Designed for Agriculture (RD4AG) in Yuma, Arizona, and I was presented with the opportunity to gain a better understanding of Integrated Pest Management (IPM) and production practices in the low deserts of Arizona. RD4AG is an independent contract research organization (CRO) that focuses on the assessment, development and regulatory aspects of new agribusiness industry technologies. As a Biological Research Intern, I was given the responsibility of overseeing multiple contracted trials from start (planting) to finish (report). Most trials focused on the efficacy of potential IPM products. Trials were conducted on a variety of crops including tomato (*Solanum lycopersicum* L.), bell pepper (*Capsicum annuum* L.), cantaloupe (*Cucumis melo* L.), squash (*Cucurbita* spp.), alfalfa (*Medicago sativa*) and cotton (*Gossypium* spp.).

The majority of my experience with RD4AG occurred in the Yuma Valley and Imperial Valley. These valleys are on either side of the Colorado River that runs along the Arizona-California border in southeastern California and southwestern Arizona near the city of Yuma, Arizona. Therefore, this document will focus on IPM of specific crops grown in this arid region.

Arid lands like the low desert valleys of the southwestern United States make up a large portion of the arable land used for agricultural purposes. Arid lands are defined by their rainfall and temperature, and separated into three categories: extremely arid (hyper-arid), arid, and semi-arid (Salem 1989, Walker 1996). Approximately one-third of the total land area of the world can be classified as arid land (Salem, 1989). Agricultural production in arid zones is possible only if irrigation is available.

Extremely arid zones are categorized by the lack of rainfall for at least 12 consecutive months (Salem 1989, Walker 1996). Arid lands receive an annual rainfall of less than 250 millimeters (9.8 inches)(Salem 1989, Walker 1996). Semi-arid lands receive a mean annual rainfall of 250-500 millimeters (9.8-19.6 inches) and are able to support rain-fed agriculture (Salem 1989, Walker 1996). Arid and extremely arid lands are considered deserts, and semi-arid lands are often referred to as grassland (Walker 1996). To provide perspective, the Nebraska sandhills are categorized as semi-arid since they receive approximately 500 millimeters (19.6 inches) of rainfall annually (Walker 1996). Arid regions typically have warm climates; therefore, they provide an opportune environment to extend the growing season and grow a broad and diverse range of productive crops (Silvertooth, 2005).

Crop production is possible in the arid lands of the low desert region of the southwest United States by irrigation from the Colorado River (Sanchez, Zerihun, & Farrell-Poe, 2009). A variety of vegetables, field crops, and fruits are grown in this mid-latitude desert climate.

Climate in Yuma, Arizona

Yuma's weather is predominately sunshine or clear skies. On average 66% of the days of the year will be categorized as clear (Western Regional Climate Center 2010). The average summer (June to August) temperature is 33°C (91.4°F); however, for the summer months, the daily temperature typically exceeds 40°C (104°F)° (Western Regional Climate Center 2010). The temperature usually reaches 36-40°C (97-104°F) digits by 10:00 am and for this reason most outside labor forces start work at 4 -5 am during the summer months. In contrast, the average winter (November to January) temperature is 15°C (59°F) with daily maximums reaching into the 20's (68°F plus) (Western Regional Climate Center 2010). The record low for the Yuma Valley was set in January of 2007 at a temperature of -10.5°C (13°F) (Western Regional Climate Center 2010). The record high was set in July 1995 with a temperature of 51°C (124°F) (Western Regional Climate Center 2010).

Yuma is considered one of the driest and least humid places in the United States. The city of Yuma and the Yuma Valley receive an average annual rainfall of 80.5 millimeters (3.17 inches)(Western Regional Climate Center 2010). On average, there are 17.1 days out of the year that have recorded precipitation (Western Regional Climate Center 2010). When rain falls in Yuma it becomes an event and everyone stops what they are doing to admire the moment. It is not uncommon for part of the valley to receive rainfall while other areas do not.

The Yuma Valley has an elevation of 120 feet and the Yuma International airport and military base are at 210 feet above sea level (Western Regional Climate Center

2010). Crops are grown in two locations around the city of Yuma that are associated with these elevations. The majority of the vegetable crops are grown in the valley, which is at a lower elevation. The Mesa is where the airport is located and majority of the crops grown in this area are perennial (e.g. citrus, alfalfa).

Yuma County & Yuma Project

The western border of Yuma County is formed by the Colorado River with California to the west and Mexico to the south. The County is approximately 5,522 square miles in size and is predominately open desert (Yuma County, 2009).

The Yuma Project provides irrigation water that has been diverted from the Colorado River to agricultural lands surrounding the towns of Yuma, Somerton, and Gadsden, Arizona and the towns of Bard and Winterhaven, California (Bureau of Reclamation, 2012)**.** The project was originally divided into two divisions. The Reservation Division encompasses approximately 14,676 acres in California, and the Valley Division irrigates approximately 53,415 acres in Arizona (Bureau of Reclamation, 2012). The project features the Laguna Dam on the Colorado River, the Boundary Pumping Plant, an unnamed powerplant, and a large system of canals, laterals, and drains. The main canals (West Main, Central, and East Main) and an additional 218 miles of lateral canals deliver water to individual fields and farms (Bureau of Reclamation, 2012). Since 1948, the Laguna Dam has not been used as a diversion structure. The water that fills the Yuma Project canals is currently diverted from the All-American Canal. The All-American canal is filled with water that is diverted from the Colorado River at the

Imperial Dam (Bureau of Reclamation 2012). The Imperial Dam was put in place upstream of the Laguna Dam in 1930 (Bureau of Reclamation 2012).

The Yuma County Water User's Association (YCWUA) manages the Valley Division of the system, and the Bureau of Reclamation manages the Reservation Division. The YCWUA was founded in 1903 and assumed responsibilities of the Valley Division from the Bureau of Reclamation in January 1963 (Bureau of Reclamation, 2012). The first water from the Colorado River through the Yuma Project was delivered to fields on the Arizona side on June 29, 1912 (Bureau of Reclamation, 2012).

Low Desert Crop Production Practices

Yuma County is known as the "Winter Salad Bowl." Approximately 90 percent of the United States leafy vegetables are grown in Yuma County from the months of November to March. Due to this winter vegetable production, Yuma is home to nine plants that produce bagged lettuce and salad mixes. These plants process approximately two million pounds of lettuce per day.

Crop Rotations

Fields do not remain fallow in the low desert valley for extended periods. If they are fallow it is typically because tillage or leveling is being done to prepare the field for the next crop. Vegetable crops are either being planted or harvested through the year and many are grown adjacent to one another (Figure 1.1). The primary crop for the Yuma

Valley from September to April is greens (e.g. leaf lettuce, head lettuce, spinach, etc.). Fields that are often in lettuce production two thirds of the year are planted to summer cover crops like Sudangrass (*Sorghum sudanense* (Piper) Stapf.)(Wang and Nolte 2010). Sudangrass is grown for hay and seed production, but following the last cutting, it can provide additional carbon and nitrogen for the following crop when tilled into the soil (Wang and Nolte 2010). In addition to summer cover crops, some lettuce fields will be rotated out of production and planted with longer season field crops (e.g. wheat, cotton, sugarbeets).

Field and vegetable crops are not the only cultivated crops grown in the low desert valleys of Arizona and California. Fields planted to perennial crops like citrus and dates are also located in the valleys. The approximate blooming and harvest dates for these crops can be observed in Figure 1.2.

Soil and Bed Preparation

Yuma Valley and the Imperial Valley have a variety of soil types. Lighter soil textures include loamy sand and sandy loam; whereas, the heavier soils are clay loam (Kerns, et al., 1999). The fields are typically deep chiseled and laser leveled after each cropping season. The deep chiseling of the field allows for proper internal drainage and helps to reduce salt accumulation in the soil profile (Kerns, et al., 1999). Laser leveling makes irrigation more efficient and reduces run off from furrow-irrigated fields (Daubert & Ayer, 1982). Individual fields are often flooded after leveling and before planting to facilitate salt leaching and volunteer or weed seed germination (Figure 1.3). Following

the flooding, the field is tilled to a depth of approximately 10 to 12 inches by moderate to extensive disking (Kerns, et al., 1999). During or immediately following disking, pre-plant herbicides and/or starter fertilizers are applied. After tillage, the rows are listed and beds shaped for planting (Figure 1.4).

Fertility and Irrigation

Fertilizer applications are similar to other areas and crops grown throughout the United States. Fertilizer is shanked into the root zone during planting or side dressed during the growing season. Fertigation is a common practice in low desert crop production where nutrients are added directly to the irrigation water before the water is delivered to the crop. In low desert production this may be through injection into a pipe/sprinkler system, drip irrigation, or just added to furrow irrigation water.

In Yuma County, water is delivered by the YCWUA to individual fields and farms via the Yuma project system. The water is cycled through multiple concrete lined canals and metal gates. The gates are coded and the farmer or farm manager must contact YCWUA to order water for a particular field. There are only a few days a year that no water can be ordered because of canal maintenance.

The most efficient irrigation system for low desert crop production is pressurized subsurface drip (Sanchez, Zerihun, & Farrell-Poe, 2009). However, this system can become an issue with crop rotations and cultural practices. In an individual field with a continual rotation of different crops that vary in architecture and growth period, it can be difficult to implement a drip irrigation system because of the dirt work that may be

involved between crops. Some crops may require that the field be chisel plowed to allow for the root systems to be broken up, but another crop may only require a shallow disking to prepare for the next cultivation. Therefore, furrow-irrigation and sprinkler systems remain the primary method of irrigating crops in the Lower Colorado River Region (LCRR) (Sanchez, Zerihun, & Farrell-Poe, 2009). Sprinkler systems are principally used at the beginning of the crop to aid in germination and proper stand establishment (Figure 1.5). Following stand establishment, the portable sprinkler systems are removed and the crop is watered by furrow irrigation.

Furrow irrigation in the low desert regions of the southwest United States is a mix of “classical” furrow irrigation and flood irrigation. Closed-end level furrows are produced between the beds of developing vegetables (Sanchez A et al. 2009). These furrow are often packed at the bottom by machinery to encourage water movement into the beds. Water is released into one end of the field through surge irrigation or into individual furrows via a pipe until the furrows are filled with water to a certain height. The water level is often only inches from the top of the bed. The water is then allowed to slowly infiltrate the soil profile. Depending on the irrigation strategy, every furrow may be filled or every other furrow. This procedure is done multiple times until the crop reaches maturity.

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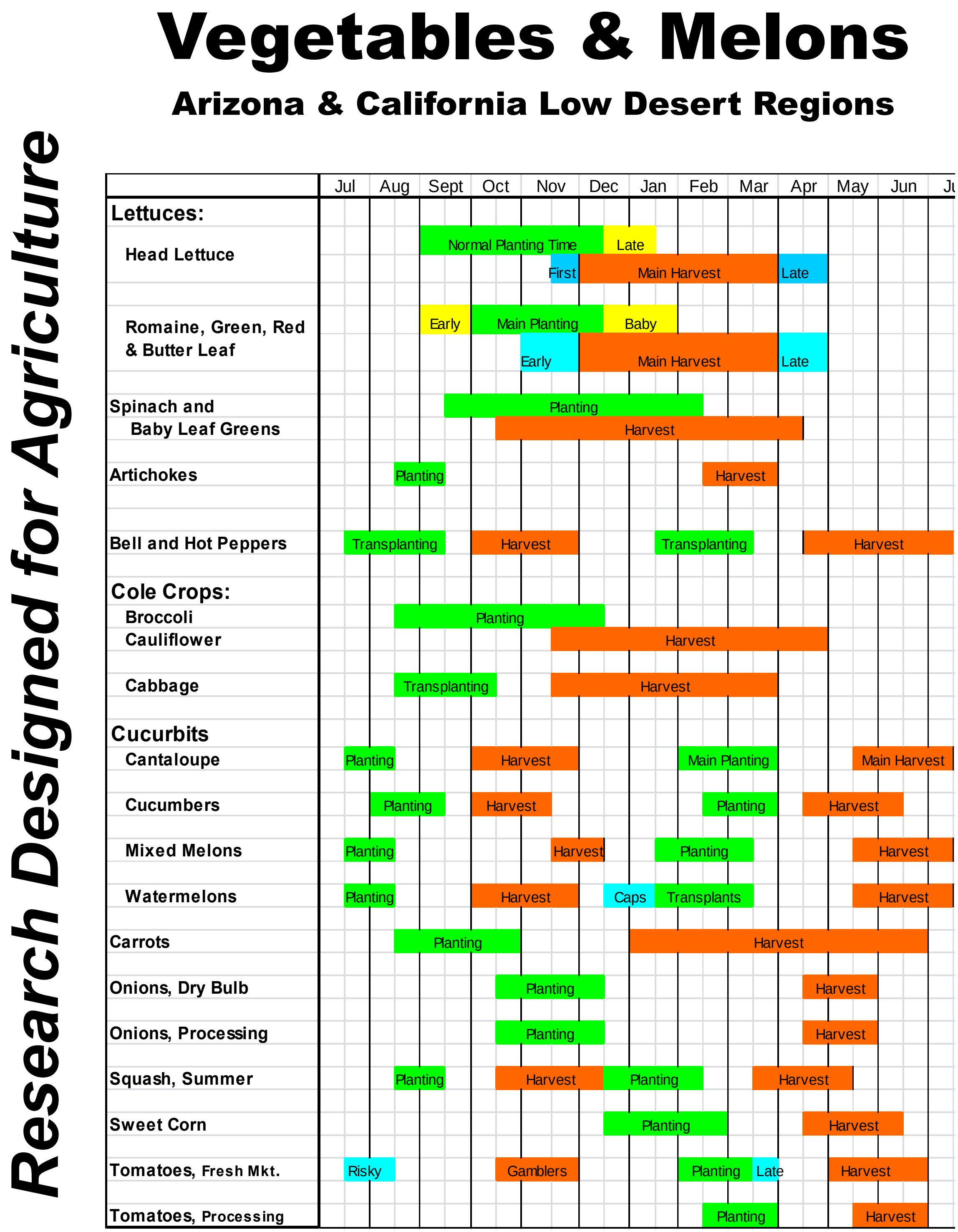

Figure 1.1 - Vegetable and melon cropping schedules for low desert regions of Arizona and California (With permission from Lee & Steve West, RD4AG, 2014).

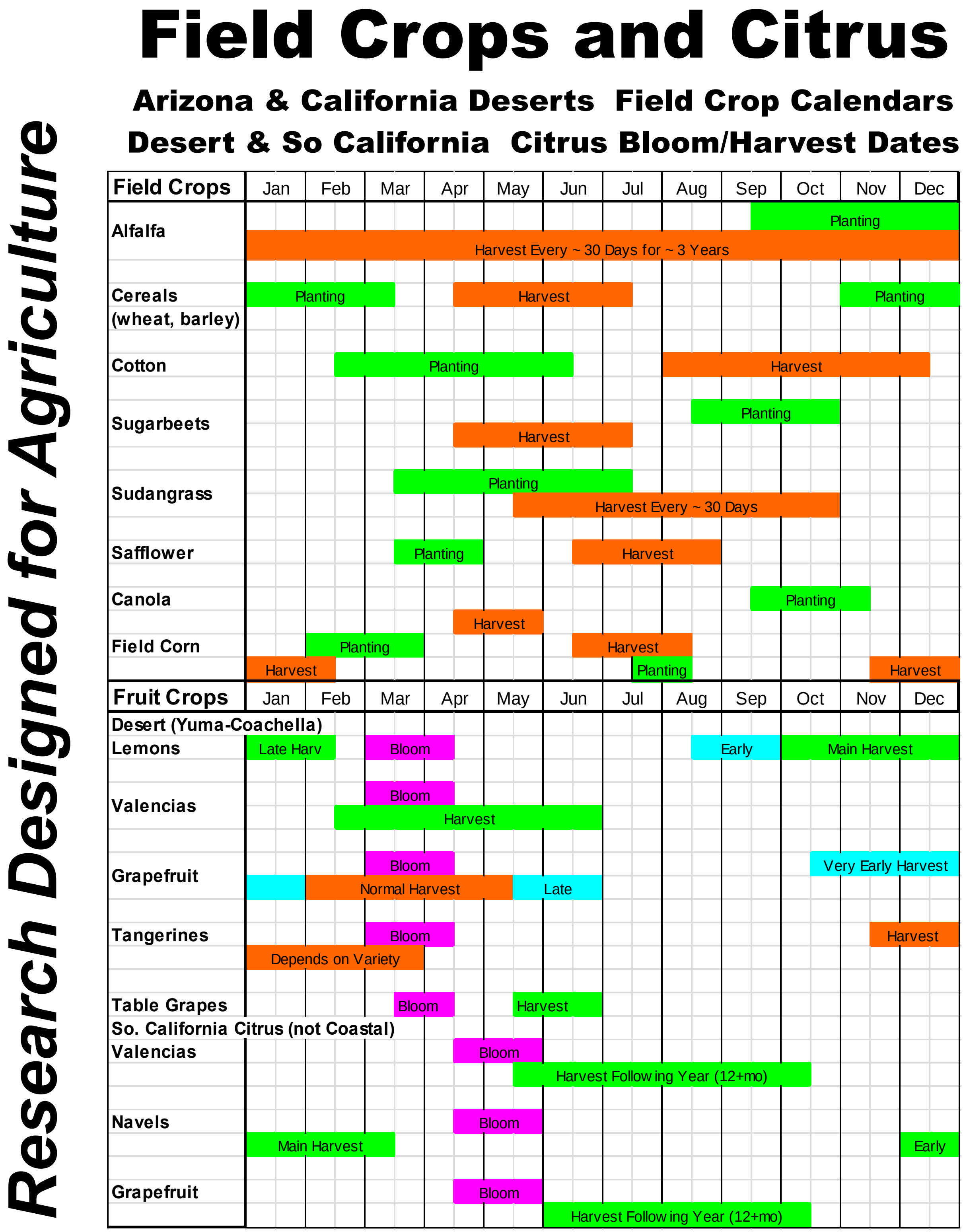

Figure 1.2 - Arizona and California field crops and citrus schedules (With permission from Lee & Steve West, RD4AG, 2014).

Figure 1.3 - Individual field flooded after leveling to facilitate salt leaching and volunteer or weed seed germination. Photo by Jeremy Wagnitz.

Figure 1.4 - Beds being listed and shaped after soil has reached desired consistency from tillage. Photo by Jeremy Wagnitz.

Figure 1.5 - Sprinkler irrigation system used after planting to help promote germination and stand establishment. Photo by Jeremy Wagnitz.

CHAPTER 2

PEST FACTORS AFFECTING VEGETABLE CROP PRODUCTION

Pests can be major factors affecting crop production and crop yields. A pest is an organism that has the ability to reduce the abundance, value and/or quality of a crop (Bailey et al. 2010). An organism is given pest status when the population or activity of the organism clashes with human needs (Flint 2012). Any organism can gain pest status; however, organisms classified as crop pests typically include plant pathogens (e.g., fungi, bacteria, viruses, nematodes), weeds, arthropods (e.g., insects, mites), and a few vertebrate species (e.g. rodents).

Not all organisms found in an agroecosystem are crop pests. Some of these organisms can be beneficial or of no consequence to the area being managed. However, diverse communities of pest species do exploit crops of all types and varieties. The composition of the crop pest community varies both on a large scale (region to region) and small scale (field to field).

Common Arthropod Pest

Although there are multiple vegetable crops grown throughout the year in the low desert valleys of California and Arizona my experience as an intern at Research Designed for Agriculture (RD4AG) in the summer of 2013 only allowed me to be introduced to the

production of and issues related to production of a few select crops. The crops in this section of the document were selected, because they were the crops I worked more thoroughly with during my time at RD4AG in Yuma, Arizona.

The arthropod pests for each specific crop in this section were chosen for several reasons. These pests are common in the production of these specific crops in the low desert valleys of California and Arizona, but more specifically the Yuma Valley in Arizona. A table that provides a more thorough list of arthropod pests is available for each crop at the end of the chapter.

Tomato Production

Fresh market tomatoes are a relatively minor crop in the Yuma Valley. However, in the adjacent Imperial Valley in California there is a larger amount of production. The production is still relatively minor at only 5% of the overall fresh market production in the state of California (LeBoef et al. 2000). The pests detailed below can cause severe damage to the crop in this region of California's tomato production. A more thorough list of arthropod pests in tomatoes for the southwestern United States can be found in Table 2.1.

Cutworms (Lepidoptera: Noctuidae)

The two most prominent cutworm species in tomatoes are the Variegated cutworm (*Peridroma saucia* Hübner) and the Black cutworm (*Agrotis ipsilon* Hufnagel).

Both species exhibit holometabolous metamorphosis. The larval life stage is the damaging stage to crops. Fields that have higher levels of organic debris on the surface are more prone to injury as the adult moths prefer to deposit eggs in the residue (Palumbo and Kerns 1998).

Developing larvae can vary in both color and patterns. However, they will always appear to have smooth skin to the naked eye. The mature larvae are 1 to 2 inches in length and feed at night (Martin and O'Neill 2011). During daylight hours the larvae will remain hidden under debris or in the soil at the base of the host plant (Martin and O'Neill 2011). The larvae when disturbed will often curl up into a crescent shape (Palumbo and Kerns 1998).

Feeding by the developing larvae causes damage to the crop. Stand loss may occur early in the season due to larvae cutting off seedlings or transplants at the soil line (Martin and O'Neill 2011). In addition to causing damage to the plants at the surface, early instar larvae of the variegated cutworm also climb plants and feed on leaves (Sorensen and Baker 1994). Damage may occur later in the season as the larvae feed on the fruit. The feeding damage will appear as irregular holes in the surface of the fruit (Martin and O'Neill 2011). Tomatoes closest to or on the ground are generally the most seriously injured (Martin and O'Neill 2011).

Silverleaf whitefy (Hemiptera: Aleyrodidae)

There are several species of whiteflies that can attack tomatoes. In the low desert growing regions of the North American southwest, the silverleaf whitefly (*Bemisia*

argentifolii Bellows & Perring) is the most problematic. This species was originally believed to have been a new strain of the sweetpotato whitefly (*Bemisia tabaci* Gennadius).

Whiteflies exhibit intermediate metamorphosis with egg, nymph, and adult. However, the four instars are described differently for the Aleyrodidae family. The first instar is mobile and referred to as “crawlers” (Palumbo and Kerns 1998). This instar is commonly yellowish in color and oval or flattened (Palumbo and Kerns 1998). The other three instars are immobile and can be described as “scale like.” The fourth instar is referred to as the pupa or red-eye nymph (Martin and O'Neill 2011). This stage of development is the easiest to identify because of the distinctive red spots that resemble eyes. Silverleaf whitefly pupae tend to be oval, whitish, and soft in appearance; however, there are no waxy filaments coming from the edge of the pupal case (Palumbo and Kerns 1998, Martin and O'Neill 2011). The lack of waxy filaments helps in proper identification of the pest.

The adult silverleaf whitefly is a small insect (ca. 1-1.5 mm long) with a yellowish body and white wings (Martin and O'Neill 2011). The adult silverleaf whitefly is unique in that the wings are held in a vertical or rooflike orientation over the body. Other whitefly species hold their wings in more of a flat orientation (Martin and O'Neill 2011). When plants are disturbed, the adults are seen flying around the infested host plant.

The silverleaf whitefly causes injury to the host plant through their feeding. Both the adult and nymphs feed on the leaves of the plant by inserting their piercing sucking

mouthparts into the vascular tissue of the leaf to extract nutrients from the plant in the form of carbohydrates and amino acids (Palumbo and Kerns 1998). This feeding causes the leaf to yellow and curl (Martin and O'Neill 2011). Heavy infestations cause significant damage to the chlorophyll in the leaf, reducing photosynthetic activity of a plant (Palumbo and Kerns 1998).

In addition to reduced photosynthesis from feeding, the whitefly produces a sugary substance called honeydew. Honeydew can collect on the leaf surface and cause the leaves to take on a shiny or blackened appearance. The blackened appearance is due to the growth and development of sooty mold (Martin and O'Neill 2011). The growth of sooty mold on the leaf's surface can also contribute to the reduction of photosynthetic activity of the infested leaf.

Furthermore, *Bemisia* species of whiteflies are known to be vectors of plant viruses. The silverleaf whitefly can transmit gemini viruses such as *Tomato yellow leaf virus* (Martin and O'Neill 2011). Viruses transmitted by whiteflies can cause additional injury and loss. These viruses transmitted by the silverleaf whitefly are often more devastating to the crop than direct feeding by the insect vector. Often the vector may be controlled and the feeding damaged, prevented, or reduced, but the virus and the symptoms it causes can not be cured or reduced. These symptoms then lead to additional yield losses after the vector has been managed.

Bell Pepper Production

Similar to tomatoes, bell (sweet) peppers are a minor crop for the Yuma Valley. The insect pests selected for a more detailed review were chosen for a few different reasons. These pests are common in the pepper production in the low desert valleys of California and Arizona and have the ability to migrate from Mexico from alternate hosts grown during different cropping seasons. A table that provides a more thorough list of arthropod pests is available for peppers in Table 2.2 at the end of the chapter.

Green Peach Aphid (Hemiptera: Aphididae)

The green peach aphid (*Myzus persicae* Sulzer) is found worldwide. The green peach aphid has a wide host range and can be found on ornamental plants, weeds, and agronomic crops. The species can be found throughout the year in low desert valleys, but it is more prevalent from March through May and September through November when lettuce is being grown (Basler and Lang 2012).

Aphids exhibit paurometabolous development, which is where the nymphs and adults live in the same terrestrial habitat. The life cycle consists of egg, nymph, and adult. The eggs of the green peach aphid are yellow or green and begin to turn black as they develop (Kuhar et al. 2009). The nymphs are yellow or green in color and closely resemble adults, but are smaller in size. Nymphs in the colony that will develop into winged adults develop a pinkish coloration (Kuhar et al. 2009, Basler and Lang 2012).

Adult green peach aphids develop into two separate mature forms. The wingless adults are yellowish to greenish in color and have prominent cornicles on the abdomen

that are swollen and club shaped (Kuhar et al. 2009, Basler and Lang 2012). The winged adults have a black head and thorax in addition to a distinct dark patch on the tip of their abdomen and a yellowish green abdomen (Kuhar et al. 2009). Egg-laying females or oviparae are pinkish in color and larger in size (Kuhar et al. 2009).

Green peach aphid adults and nymphs cause damage by sucking sap from the host plant during feeding. The colony primarily feeds on the underside of newer and younger leaves in the center of the plant canopy (Basler and Lang 2012). Excessive feeding causes young plant tissues to develop water stress and wilt. If the feeding is extensive the plant tissues may turn yellow and the leaves will curl downward and inward from the edges (Basler and Lang 2012).

In addition, to the direct injury caused by the aphid, aphids produce honeydew similar to the silverleaf whitefly mentioned previously. Honeydew is especially problematic for fresh market peppers (Basler and Lang 2012). Honeydew is produced in large quantities by the aphid and is expelled from their bodies through the cornicles on their abdomens.

Furthermore, the green peach aphid has been documented to vector multiple viruses. Two destructive viruses for peppers transmitted by the green peach aphid are pepper potyviruses and cucumber mosaic cucumovirus (Kuhar et al. 2009, Basler and Lang 2012). The transmission of virus is one of the major concerns with aphid infestations.

Pepper Weevil (Coleoptera: Curculionidae)

The pepper weevil, *Anthonomus eugenii* Cano, is an important pest of peppers in the United States' southern most states. The species is believed to have originated in Mexico, but has migrated into Texas, New Mexico, Arizona, California, and Florida (Sorensen and Baker 1994). The species is a common and important pest of peppers in southern California and Arizona (Basler and Lang 2012).

As a coleopteran pest, the pepper weevil exhibits holometabolous development. The eggs are white when first deposited, but turn yellow as development occurs (Capinera 2013). The female deposits the eggs by creating a cavity with her mouthparts just beneath the surface of a flower bud or pod (Basler and Lang 2012, Capinera 2013). In three to five days, eggs hatch and the larvae feed on pod wall (Basler and Lang 2012). The larvae continue development through three instars inside of the infested fruit, and then they create a pupal cell (Capinera 2013). After pupation the adult weevils emerge from the infested fruit through a round hole. Pepper weevils are reddish-brown to black in color and have a long curved snout, which is common of the genus.

Pepper weevils cause injury to a pepper plant by feeding on the foliage, blossom buds, and immature pods. Larvae tend to feed on the seed core, but can also feed and tunnel into the wall of developing pods (Sorensen and Baker 1994). This feeding causes the core to become brown and moldy. In addition to the feeding damage, the inside of the developing fruit becomes contaminated with frass (Capinera 2013). Stems of the infested pods will turn yellow and the fruit or pod will prematurely ripen (Capinera 2013). Infested blossom buds and smaller fruits will prematurely drop, reducing yield (Basler and Lang 2012). However, larger infested fruit may not drop, resulting in a contaminated crop (Basler and Lang 2012).

Fruit drop is usually the most obvious sign of an infestation, and this also has the greatest yield impact. However, if the pest population is present and there is an absence of blossoms or developing fruit the adult weevils will feed on leaves and young stems (Capinera 2013); however, this damage is usually not significant. If mature fruits are present, adults will feed on the surface of the fruit causing punctures that allow pathogens to develop.

Cantaloupe Production

Melon production in the southwest United States occurs in a diverse cropping environment that includes a variety of vegetables and field crops being grown simultaneously throughout the year. Cantaloupe are commonly grown in two distinct growing seasons. Fall melons are usually planted from July to September; whereas, spring melons are planted from January to March (Palumbo and Kerns 1998). There are a number of insect species that can be found in a melon field or on a melon plant. A more thorough list of arthropod pests is available in Table 2.3.

The majority of the economically important insect pests of cantaloupe are polyphagous and typically migrate from surrounding crops and/or weed host (Palumbo and Kerns 1998). These insect pests can be divided into four groups: ground dwelling, foliar feeding, sucking, and fruit feeders (Palumbo and Kerns 1998).

Melon Aphid (Hemiptera: Aphididiae)

The melon aphid, *Aphis gossypii* Glover, is also known as the cotton aphid and can be an issue for both spring and fall melon production. The aphid is relatively small (~1.5 mm in length) and can range in coloration from yellowish green to greenish black (Basler et al. 2013). This aphid species is regularly a pest in the southeastern and southwestern United States.

Aphids exhibit paurometabolous development. The life cycle consists of egg, nymph, and adult. The eggs of the melon aphid are yellow when deposited, but quickly become shiny black during development (Capinera 2012). Nymphs range in color from tan to gray or green. The coloration of the body tends to be dull due to wax secretions (Capinera 2012).

Similar to the green peach aphid, melon aphid adults exhibit two mature forms. The wingless (apterous) adult females vary widely in color from shades of green to white or yellow (Capinera 2012). The cornicles and the tips of the legs (tibiae and tarsi) are black (Capinera 2012). The winged (alate) adult females have distinct black heads and thoraxes with yellowish green abdomens (Capinera 2012). The winged form is commonly less robust than the wingless form (Basler et al. 2013). Oviparae females are dark purplish green in color (Capinera 2012).

Melon aphids can be a major issue for young plants both in the fall and spring plantings, as they tend to congregate on the terminal growing point. In addition to feeding on the growing points, they will cluster on the underside of the leaf (Basler et al. 2013). Adults and nymphs feed by sucking sap from the plant host. This feeding causes developing leaves to distort and curl (Palumbo and Kerns 1998). As the aphid feeds, it

produces honeydew, providing an environment for the growth and development of sooty mold. The combination of the feeding and growth of mold on the leaves' surface can reduce the plant's photosynthetic rate.

Like the green peach aphid, the melon aphid is known to vector multiple viruses. Viruses commonly transmitted by the melon aphid include cucumber mosaic, zucchini yellow, watermelon mosaic, and other potyviruses (Palumbo and Kerns 1998, Capinera 2012, Basler et al. 2013). Damage due to a virus can still occur after the aphid population has been controlled or moved since the aphid vector transmits the virus to the plant in as little as 15 seconds (Capinera 2012).

Cabbage Looper (Lepidoptera: Noctuidae)

Cabbage loopers, *Trichoplusia ni* Hübner, can be a very destructive pest in melon crops. The species can be a pest in both spring and fall melon production, but is more prevalent in the fall (Palumbo and Kerns 1998). This insect species can be found throughout the United States, Mexico, and Canada (Capinera 2014).

The lepidopteran species exhibits holometabolous development. The eggs are yellowish white or green and are deposited singly on the underside of leaves (Palumbo and Kerns 1998, Basler et al. 2013, Capinera 2014). The eggs are dome shaped, but flattened on the side attached to the leaf surface (Palumbo and Kerns 1998). Young larvae that emerge from the eggs are dusky white color, but will become pale green as they begin to feed (Capinera 2014). Developing larva will go through five instars. The

mature larva is green with distinct white stripes along its sides (Capinera 2014). Mature larvae can measure between 3-4 cm (1-1.5 in) in length (Capinera 2014).

The larvae have two separate sets of legs. Near the front of the body there are three pairs of thoracic legs, and near the rear of the larvae there are three pairs of unjointed abdominal prolegs. The insect's common name comes from the way these pairs of legs are used by the insect to move. The larvae will crawl forward with its prolegs while arching its back. The arching will cause the formation of a "loop." At this time, the front section will be lifted and in turn projecting the larvae forward.

Before pupation the larvae form a white cocoon on the underside of a leaf, in debris, or between clods of soil. Emerging adult moths have mottled gray-brown forewings and hind wings that are light brown on the base (Capinera 2014). The adult moth has a wingspan of 33-38 mm (1.2-1.5 in) (Capinera 2014). The forewings have distinct silvery spots in the center that forms a figure 8 (Palumbo and Kerns 1998, Capinera 2014).

Cabbage looper larvae begin feeding on the underside of leaves, causing an injury described as skeletonizing (Basler et al. 2013). As the larvae get larger (fourth and fifth instar) they will begin to chew ragged holes into the leaf, but rarely feed on the leaf margin (Palumbo and Kerns 1998, Capinera 2014). Feeding sites can often be covered in a sticky, wet frass (Capinera 2014). During fall melon production, populations can be high, and this can lead to seedlings being severely damaged and the crop maturing at different rates (Palumbo and Kerns 1998). Heavy larval populations also feed on the

netted surface of developing cantaloupe, which can cause cosmetic blemishes (Palumbo and Kerns 1998).

Common Plant Pathogens

This section will cover pathogens that have the potential to cause disease issues for these crops in the desert valley regions of California and Arizona. The diseases chosen for this section show the diversity of pathogen types (i.e. bacterial, fungal, and viral) that affect these types of crops in arid environments. More complete lists of diseases that may need to be managed for these specific crops can be found in tables provided at the end of the chapter.

Tomato Production

Field tomato production is a minor crop for the Yuma Valley area, but is in larger production in the adjacent Imperial Valley of California. The pathogens chosen for additional detail below cause severe damage to the field crop in California's desert growing region and to transplants produced in the Yuma Valley for other growing regions. A more thorough list of pathogens known to cause diseases in tomatoes for the southwestern United States can be found in Table 2.4.

Fusarium Wilt

The fungal pathogen that causes the disease Fusarium wilt in tomatoes is *Fusarium oxysporum* f. sp. *lycopersici*. Fields with high incidences of Fusarium can have large reductions in yield (Martin and O'Neill 2011). There are three known races (e.g., Race 1, Race 2, and Race 3) of *F. o. lycopersici* (Elias and Schneider 1991).

The fungus infects the host plant through the roots and invades the xylem. As the xylem becomes infected individual branches and associated leaves will become yellow and wilted (Martin and O'Neill 2011). A characteristic symptom called "yellow flag" can occur as only one side of the plant may be affected by the infection (Martin and O'Neill 2011). As the infection progresses, a dark brown discoloration will occur on the surface of the stem from the vascular infection. Once infected, plants usually die before maturity (Miller et al. 1996b).

The fungal spores survive for many years in the soil, but spores can also be carried long distances by seed, transplants, and in soil attached to farm equipment (Martin and O'Neill 2011). Fusarium wilt has become less of an issue in field-grown tomatoes because of the use of resistant varieties; however, as consumers' interest in "heirloom" varieties continues to increase, the disease may become more significant (Miller et al. 1996b).

Bacterial Spot

The causal organism of the disease bacterial spot is *Xanthomonas campestris* pv. *vesicatoria.* This is a motile bacterium that is aerobic, gram negative, and has one polar flagellum (Obradovic et al. 2008).

Bacterial spot symptoms can be seen on leaves, stems, and fruits during all stages of growth on the tomato plant (Langston 2010). Lesions on the leaves usually begin as small water-soaked areas that eventually become necrotic in the center (Reiners and Petzoldt 2014). Infected leaves will eventually develop a scorched appearance (LeBoef et al. 2009). Premature leaf drop will occur due to lesion formation (Langston 2010).

Flower abortion may occur if the infection site is located on the pedicel of the flower (Reiners and Petzoldt 2014). Lesions can also develop on the green fruit. These lesions are small and dark brown to black in color (LeBoef et al. 2009). As lesions develop it becomes raised and approximately 1/8 to 1/4 inch in diameter (Reiners and Petzoldt 2014). As the fruit matures, the lesions begin to sink in the middle and take on a scabby appearance (Miller et al. 1996a).

Bacteria persist in the soil on infected plant debris (Miller et al. 1996a). The bacteria can also survive on seeds and can be transferred to fields by transplants that were direct seeded in the greenhouse (Obradovic et al. 2008). Primary spread occurs through wind and rain that provides opportunities for the bacteria to enter the plant through natural openings (stomata, hydathodes) or wounds (mechanical, insect) (Reiners and Petzoldt 2014).

Bell Pepper Production

Field production of bell (sweet) peppers is a minor crop for the Yuma Valley region. However, California led the country with approximately 23,400 acres planted in

2013 (USDA, National Agricultural Statistics Service 2013). The following pathogens were chosen for further detail to provide examples on the how cultural practices (i.e. plastic mulched bed) and management of pests (i.e. insect vectors) can influence the potential for disease issues in a crop. A more thorough list of pathogens known to cause disease in bell peppers in the desert southwest can be found in Table 2.5.

Beet Curly Top

Beet curly top virus (BCTV) is common throughout the arid and semi-arid regions of the western United States. The virus is a single stranded DNA virus that belongs to the family Geminiviridae (Goldberg 2001). BCTV has a wide host range, including over 300 plant species (Goldberg 2001).

The virus name is descriptive of the symptoms that the host displays when infected. Infected plants are chlorotic and stunted (Basler and Lang 2012). The top of the infected plant will resemble a rosette or smaller sized flower bouquet (Basler and Lang 2012). As the infection continues to develop the leaves will thicken and roll upward while the petioles curve downward (Goldberg 2001). The fruit of infected plants will remain in an upward orientation and not droop (Basler and Lang 2012). Infected plants will not recover and will remain stunted with reduced yields (Heflebower et al. 2012). Plants infected at an early stage of development may die. Infected plants in a pepper field are commonly scattered.

The sugarbeet leafhopper (*Circulifer tenellus* Baker) vectors the virus for life after acquiring the virus by feeding on an infected host plant (Martin and O'Neill 2011). The

leafhopper commonly moves into production fields from weedy areas that serve as an alternate food source. Weed species that are alternate hosts for the leafhopper include Russian thistle (*Salsola tragus* L.), Kochia (*Kochia scoparia* L. Schrad.), and Lambsquarter (*Chenopodium album* L.) (Heflebower et al. 2012).

Phytophthora Blight

The fungus, *Phytophthora capsici,* causes the disease Phytophthora blight in peppers. This pathogen affects all parts of the plant and is also commonly referred to as Phytophthora root rot, crown rot, or fruit rot (Zitter 1989). Under certain conditions the pathogen can also cause a brown foliar blight (Basler and Lang 2012).

The fungus occurs naturally in the soil and becomes an issue in soils with excess moisture (Zitter 1989). Phytophthora blight or rot in peppers is favored by humid and warm environmental conditions (Roberts and French-Monar 2006). The optimum temperature for the pathogen is approximately 24° to 33°C (75° to 92° F) (Roberts and French-Monar 2006, Basler and Lang 2012). Water is required for infection, and soil saturation for as little as 5 to 6 hours can result in susceptible varieties developing disease (Basler and Lang 2012).

The fungus survives in the soil for extended periods. The thick-walled survival structures called oospores will germinate and infect seedlings or transplants (Zitter 1989). The fungus will begin to develop structures called sporangiophores, on the leaves of the infected plant (Zitter 1989). Sporangiophores develop sporangia that can be dispersed to healthy plants by rain splash, surface water, or wind. The sporangia can infect the plants

directly or with adequate moisture, they can develop biflagellate motile zoospores (Zitter 1989). These zoospores can easily move through saturated soils to infect neighboring plant roots or down furrows with surface irrigation water. These environmental conditions and fungal structures are the reason that the disease often occurs first in low areas where water may accumulate (Zitter 1989, Roberts and French-Monar 2006).

Plants in a row or in a circular pattern will often show symptoms of infection at about the same time due to the way the pathogen is dispersed. Plants infected at an early growth stage (prior to bloom) will quickly die (Zitter 1989). If plants are infected during a later (bloom to fruit set) stage of growth they will exhibit an irreversible wilting symptom (Zitter 1989). The leaves and stems can both develop symptoms associated with the infection. The leaves may develop circular to oval shaped lesions that look water-soaked (Roberts and French-Monar 2006). The stems or crown can also develop dark green or water–soaked lesions (Roberts and French-Monar 2006, Basler and Lang 2012). Lesions on the stems may eventually turn brown and dry out, leading to the plant or plant part being girdled and killed (Zitter 1989, Basler and Lang 2012). The fungus may also attack the developing fruit and produce small lesions that quickly expand and have white sporulating mycelia present (Roberts and French-Monar 2006).

Examination of the infected plant's roots is required to correctly identify the causal agent of the disease. The roots of an infected plant will have dark brown lesions on the surface and discoloration of the vascular tissue (Basler and Lang 2012). Discoloration of the root surface is one symptom that helps to distinguish this *P. capsici* from *Verticillium dahliae* (Basler and Lang 2012). When compared to healthy plants, the

diseased plant will have a short taproot and a reduced number of lateral roots. If lateral roots are present, the majority will be located toward the soil surface because the lower roots will have likely rotted away (Roberts and French-Monar 2006).

Cantaloupe Production

California and Arizona combined in 2012 planted approximately 50% of the United States' cantaloupe acres (USDA, National Agricultural Statistics Service 2013). As discussed previously there are two separate growing periods for cantaloupe in the low desert regions of Arizona and California. These two growing periods and the intense cropping that occurs in the low desert allows for pathogens that have a wide host range to thrive. The pathogens chosen to detail further in this section are able to be placed in this type of category. Additional pathogens associated with diseases in cantaloupe can be found in Table 2.6.

Verticillium Wilt

Verticillium wilt in melons is caused by the pathogen *Verticillium dahliae.* This pathogen and another closely related species (*Verticillium albo-atrum*) are known to have a host range of over 400 plant species (Berlanger and Powelson 2005). The host range includes vegetables, herbaceous ornamentals, and woody species (Douglas 2008). The pathogen belongs to the fungal class Deuteromycetes and has no know sexual stage (Berlanger and Powelson 2005).

The disease can be an issue in irrigated crop production. The fungus is present in the soil as a structure called a microsclerotium and can persist for an indefinite amount of time even without a susceptible host being cultivated (Basler et al. 2013). When a suitable host is grown in the proximity of a microsclerotium, root exudates will stimulate germination. Once the microsclerotium has germinated, the fungus infects the host plant through the roots in the region of elongation (Berlanger and Powelson 2005) and colonize the cortex tissue of the root. Fungal hyphae grow into the xylem vessels of the root and form spore structures called conidia (Berlanger and Powelson 2005, Douglas 2008). These spores (conidia) will then be translocated throughout the host plant with water in the xylem vessels. As the vascular system becomes clogged with fungal growth and plant host defense products, the translocation of water and nutrients will be reduced. The reduction of water movement to the upper parts of the infected plant will cause wilting and foliar chlorosis (Berlanger and Powelson 2005). As the upper portions of the infected plant become necrotic, the fungus develops microslerotia that eventually reinfest the soil (Berlanger and Powelson 2005).

Verticillium wilt symptoms can vary by host; however, older leaves are often the first parts of the plant to show signs of infection. For cantaloupe, the leaves close to the crown show the first symptoms of infection (i.e. wilting and chlorosis) (Basler et al. 2013). These leaves eventually dry out as the wilting symptoms progress to the tips of the runners on the infected plant (Basler et al. 2013). Severe infections often kill the plant. Resistant or tolerant varieties will show symptoms due to infection, but they rarely die.

V. dahliae causes the vascular system of infected plants to become brown and discolored. This can be observed by cutting a cross section of the stem. The vascular

tissue will become brown, but the pith of the stem will remain white (Douglas 2008). However, this discoloration is not diagnostic because Fusarium wilt can also cause the same symptom. Laboratory culturing is required to positively identify *Verticillium*.

Downy Mildew

Downy mildew can impact desert cucurbit production, especially when irrigation practices cause prolonged leaf wetness. The disease is caused by the oomycete pathogen *Pseudoperonospora cubensis* (Becker and Miller 2009). The pathogen is a fungal-like species in the Kingdom Straminipila and the phylum Oomycota (Colucci and Holmes 2010). *P. cubensis* belongs to the family Peronosporaceae and is a biotroph (Colucci and Holmes 2010). Since the pathogen is an obligate parasite (biotroph), living host tissue is required for growth and reproduction. This pathogen can only overwinter in regions that cultivated or wild hosts are available year-round.

The pathogen's reproductive structures (sporangia) are dispersed by wind to healthy plants. Sporangia are produced singly on the end of a sporangiophore on the underside of leaves of a diseased plant (Colucci and Holmes 2010). When sporangia are deposited on the surface of a leaf, moisture triggers it to release asexual zoospores (Colucci and Holmes 2010). Zoospores are motile, and with two to six hours of free moisture on the leaf's surface, they are able to locate a stomate(Colucci and Holmes 2007, Becker and Miller 2009). At the stomate the zoospore develops a germ tube that penetrates the host and mycelium grow both intracellularly and intercellularly. The pathogen develops haustoria in the host cells, and (Colucci and Holmes 2010) nutrient

uptake through the haustoria allows for the development of new sporangiophores that commonly appear at stomatal opening on the underside of the leaf.

Downy mildew can infect plants of all ages, but commonly occurs on older leaves first. Symptoms vary by cucurbit host and are distinctively different for watermelon and cantaloupe. Leaf spots develop on the upper side of the infected leaf, and leaves eventually become necrotic and curl upward (Colucci and Holmes 2007). The lesions typically are irregular in shape and lie between the leaf venation. Leaf spots quickly turn necrotic or brown. When examining symptomatic leaves, one can observe a grayish-brown to purplish-black ‘downy’ mycelium growth (Colucci and Holmes 2007). The symptoms on cantaloupe and watermelon can often be mistaken with other diseases, such as anthracnose (*Colletotrichum orbiculare*), Alternaria leaf spot (*Alternaria alternata* f. sp. *cucurbitae*), and target spot (*Corynespora cassilicola*) (Colucci and Holmes 2010). Only the leaves of the plant are infected, but the yield of marketable fruit is reduced because of sun scald and deformed fruit.

Integrated Pest Management

Crop producers need to manage pests in order to maintain yields, quality, and profitability. Pest management involves any activities that are directed at the control of a pest or avoiding that pest’s associated damage. These activities include prevention, suppression, or eradication of the pest organism (Flint 2012).

Integrated pest management (IPM) has developed and changed over the years. The original concept of integrated pest control and the scientific basis was conceptualized

originally by researchers at the University of California, Berkeley and Riverside campuses (Bajwa and Kogan 2002). A broad range of definitions for the concept of IPM has been presented over the years. The majority of these definitions reflect the author's background and philosophies; however, most of the definitions have commonalities, such as ecologically sound principles, economic thresholds, and use of multiple tactics including chemical, cultural, and biological (Bajwa and Kogan 2002).

In 1966 the Food and Agriculture Organization of the United Nations defined integrated pest control as "a pest population management system that utilizes all suitable techniques in a compatible manner to reduce pest populations and maintain them at levels below those causing economic injury" (Smith and Reynolds 1966). A slightly less economically based definition is provided by the United States Environmental Protection Agency (US EPA).

According to the US EPA, "integrated pest management (IPM) is an effective and environmentally sensitive approach to pest management that relies on a combination of common-sense practices" (Environmental Protection Agency 2012). This definition is less detailed than others that have been developed over the past forty-nine years.

In 1981 two researchers from the University of California provided a more detailed definition of the IPM concept. "Integrated pest management (IPM) is an ecologically based pest control strategy that relies heavily on natural mortality factors such as natural enemies and weather and seeks out control tactics that disrupt these factors as little as possible. IPM uses pesticides, but only after systematic monitoring of pest populations and natural control factors indicates a need. Ideally, an integrated pest

management program considers all available pest control actions, including no action, and evaluates the potential interaction among various control tactics, cultural practices, weather, other pests, and crop to be protected" (Flint and Van den Bosch 1981, Bajwa and Kogan 2002).

Although definitions differ, the primary principles are the same. Pest management systems are multifaceted and complex because they can differ by crop, production system, locale, and the producer or practitioner's adversity to risk (Flint 2012). These systems become very dynamic and are in a constant flux due to resources, crop prices, environmental conditions, and pest resistance (Flint 2012). Regardless of the differences, IPM programs share five common components: proper identification of pest, scouting and monitoring, thresholds or action guidelines, preventative measures, and integration of management tools whether they are biological, chemical or cultural (Flint 2012).

All IPM programs strive to integrate multidisciplinary approaches to develop strategies for managing pest that are practical, effective, economical and protective of both human health and the environment (Dent 1995). The advantages of biopesticides fall in line well with the overall objectives of IPM programs. They could be used in rotation with synthetic chemical pesticides or as alternatives to these pesticides and as key components in an IPM program (Menn and Hall 1999).

Biopesticides

The EPA has specified a biopesticide or a biological pesticide as a pesticide that has been derived from natural materials, such as animals, plants, or certain minerals

(Environmental Protection Agency 2014). As of February 2014, there were approximately 400 registered biopesticide active ingredients with the EPA (Environmental Protection Agency 2014). These registered active ingredients have been formulated into approximately 1250 actively registered biopesticide products (Environmental Protection Agency 2014).

Biopesticides are organized into three classes: microbial pesticides, plant pesticides, and biochemical pesticides. Microbial pesticides have a microorganism (e.g., bacteria, fungus, virus, or protozoan) as the major active ingredient (Environmental Protection Agency 2014). Microbial-based pesticides can provide control of various pests; however, the active ingredient (microorganism) is commonly specific to the target pest. Plant pesticides or plant-incorporated-protectants (PIPs) are pesticidal substances produced by the plant due to genetic addition or modification. An example of this biopesticide type is Bt corn. The corn plant has had genetic material from the bacterium *Bacillus thuringiesis* added to its genome, and this allows the plant to produce Bt pesticidal protein on its own. Biochemical pesticides control pests by non-lethal mechanisms and are naturally occurring substances. This group of biopesticides includes products, such as insect sex pheromones, plant extracts, and certain minerals (Environmental Protection Agency 2014).

The EPA’s Biopesticides website has listed several possible advantages to the use of biopesticides including:

- Biopesticides are intrinsically less harmful than their conventional counter parts.

- Only the target pest or closely related organisms are generally affected by biopesticides. This is contrary to conventional broad-spectrum pesticides that often affect non-target organisms like birds, beneficial insects, and/or mammals.
- Often only small quantities of a biopesticide are required which will usually quickly decompose, thereby reducing exposure and pollution issues.
- As a component of an IPM program biopesticides can greatly reduce the use of conventional pesticides, while still maintaining high crop yields.

The EPA established the Biopesticide and Pollution Prevention Division in the office of Pesticide Programs in 1994 to aid in the registration of biopesticides (Environmental Protection Agency 2013). The division's primary purpose is to promote the use of safer pesticides like biopesticides as key components in IPM programs. Due to this division's work, biopesticides are often registered much faster then conventional pesticides.

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Common Arthropod Pests of Tomato

Table 2.1 Common insect and mite pests of tomato. (Martin and O'Neill 2011)

Beet Armyworm - *Spodoptera exigua* Hübner	Green Peach Aphid - *Myzus persicae* Sulzer	Hornworms - *Manduca sexta* L. - *Manduca quinquemaculata* Haworth	Potato Tuberworm - *Phthorimaea operculella* Zeller	Beet Leafhopper - *Circulifer tenellus* Baker	Stink Bugs - *Thyanta pallidovirens* Stål - *Chlorochroa sayi* Stål	Tomato Psyllid - *Bactericera cockerelli* Sulc
Western Yellowstriped Armyworm - *Spodoptera praefica* Grote	Potato Aphid - *Macrosiphum euphorbiae* Thomas	Tomato Fruitworm - *Helicoverpa zea* Boddie	Wireworms - *Limonius* spp.	Leafminers - *Liriomyza sativae* L. - *Liriomyza trifolii* Burgess - *Liriomyza huidobrensis* Blanchard	Tomato Bug - *Cyrtopeltis modesta* Distant	Tomato Russet Mite - *Aculops lycopersici* Massee
Cutworms - *Peridroma saucia* Hübner - *Agrotis ipsilon* Hufnagel	Tobacco Flea Beetle - *Epitrix hirtipennis* Melsheimer	Tomato Pinworm - *Keiferia lycopersicella* Walsingham	Loopers - *Autographa californica* Speyer - *Trichoplusia ni* Hübner	Lygus Bug - *Lygus hesperus* Knight	Whiteflies - *Bemisia arentifolii* Bellows & Perring - *Trialeurodes vaporariorum* Westwood - *Trialeurodes abutilonia* Haldeman	Garden Symphylans - *Scutigerella immaculata* Newport

Common Arthropod Pests of Peppers

Table 2.2 Common Insect and Mite Pests of Peppers (Palumbo and Kerns 1998, Basler and Lang 2012)

Armyworms - *Spodoptera praefica* Grote - *Spodoptera ornithogalli* Guenèe - *Spodoptera exigua* Hübner	Green Peach Aphid - *Myzus persicae* Sulzer	Pepper Weevil - *Anthonomus eugenii* Cano	Tomato Psyllid - *Bactericera cockerelli* Sulc	Field Crickets - *Gryllus* spp.
Darkling Beetles - *Blaspstinus* spp.	Leafminers - *Liriomyza trifolii* Burgess - *Liriomyza sativae* L.	Thrips - *Frankliniella occidentalis* Pergande - *Thrips tabaci* Linderman	Twospotted Spider Mite - *Tetranychus urticae* C.L. Koch	Cutworms - *Agrotis ipsilon* Hufnagel - *Peridroma saucia* Hübner - *Feltia subterranean* Fabricius
Flea Beetle - *Epitrix cucumeris* Harris - *Epitrix subcrinita* LeConte - *Phyllotreta pusilla* Horn - *Phyllotreta ramosa* Crotch	Omnivorous Leafroller - *Platynota stultana* Walsingham	Tomato Fruitworm - *Helicoverpa zea* Boddie	Whiteflies - *Bemisia argentifolii* Bellow & Perring - *Traileurodes vaporariorum* Westwood	Seedcorn Maggot - *Delia platura* Meigen

Common Arthropod Pests of Cantaloupe in Desert Production

Table 2.3 Insect and Mite Pests of Cucurbits (Basler et al. 2013)

Armyworms - *Spodoptera exigua* Hübner - *Spodoptera praefica* Grote - *Spodoptera ornithogalli* Guenée	Darkling Beetles - *Blapstinus* spp. - *Caelus* spp.	Grasshoppers - *Melanoplus* spp.	Melon Aphid - *Aphis gossypii* Glover	Squash Bugs - *Anasa tristis* DeGeer	Cucumber Beetles - *Diabrotica undecimpunctata undecimpunctata* L. - *Acalymma trivittatum* Mannerheim - *Diabrotica balteata* LeConte
Cabbage Looper - *Trichoplusia ni* Hübner	European Earwig - *Forficula auricularia* L.	Green Peach Aphid - *Myzus persicae* Sulzer	Seedcorn Maggot - *Delia platura* Meigen	Western Flower Thrips - *Frankliniella occidentalis* Pergande	Driedfruit Beetles - *Carpophilus hemipterus* L. - *Carpophilus freemani* Dobson - *Carpophilus mutilatus* Erichson
Field Crickets - *Gryllus* spp.	False Chinch Bug - *Nysius raphanus* Howard	Leafhoppers - *Empoasca abrupta* DeLong - *Empoasca Solana* DeLong	Spider Mites - *Tetranychus urticae* C.L. Koch - *Tetranychus desertorum* Banks	Vinegar Flies - *Drosophila melanogaster* Meigen	Wireworms - *Limonius* spp.
Cutworms - *Agrotis ipsilon* Hufnagel - *Peridroma saucia* Hübner - *Feltia subterranea* Fabricius	Flea Beetles - *Epitrix* spp. - *Systena* spp.	Leafminers - *Liriomyza sativa* L. - *Liriomyza trifolii* Burgess	Stink Bugs - *Euschistus conspersus* Uhler - *Acrosternum hilare* Say	Whiteflies - *Trialeurodes vaporariorum* Westwood - *Bemisia tabaci* Gennadius - *Bemisia argentifolli* Bellows & Perring	

Common diseases of tomato in Western United States

Table 2.4 Common diseases of tomato (Martin and O'Neill 2011, Jones et al. 2014).

Corky Root Rot - *Pyrenochaeta lycopersici* R. Schneid. & Gerlach	Alternaria Stem Canker - *Alternaria alternate* f. sp. *lycopersici* Keissl.	Gray Mold - *Botrytis cinerea* Pers.:Fr	Tobacco Mosaic (Tobamoviruses) - *Tobacco mosaic virus* - *Tomato mosaic*
Anthracnose - *Colletotrichum coccodes* (Wallr.) S. Hughes	Fusarium Crown & Root Rot - *Fusarium oxysporum* f. sp. *radicis-lycopersici* Jarvis & Shoemaker	Black Mold - *Alternaria alternata* (Fr.:Fr.) Keissl.	Alfalfa Mosaic - *Alfalfa mosaic virus*
Damping-Off - *Phytophthora* spp. - *Pythium* spp. - *Rhizoctonia* spp.	Fusarium Foot Rot - *Fusarium solani* f. sp. *eumartii* (C.W. Carp.) W.C. Snyder & H.N. Hansen	Water Mold - Pythium ultimum Trow	Mosaic Diseases (Potyviruses) - *Tobacco etch virus* - *Potato Y virus*
Late Blight - *Phytophthora infestans* (Mont.) de Bary	Fusarium Wilt - *Fusarium oxysporum* f. sp. *lycopersici* (Sacc.) W.C. Snyder & H.N. Hansen	White Mold - *Sclerotinia sclerotiorum* (Lib.) de Bary	Mosaic Virus Diseases (Cucumoviruses) - *Cucumber mosaic virus*
Early Blight - *Alternaria solani* Sorauer	Verticillium Wilt - *Verticillium dahliae* Kleb.	Powdery Mildew - *Leveillula taurica* (Lév.) G. Arnaud	Tomato Yellow Leaf Curl Virus - *Tomato yellow leaf curl virus* (TYLCV)
Southern Blight - *Sclerotium rolfsii* Sacc.	Tomato Spotted Wilt - *Tomato spotted wilt virus*	Curly Top Virus - *Beet Curly Top virus*	Tomato Infectious Chlorosis Virus - *Tomato infectious chlorosis virus*
Phytophthora Root Rot - *Phytophthora capsici* Leonian	Tomato Big Bud - Beet leafhopper transmitted viresence agent	Tomato Bushy Stunt (Tombusvirus) - *Tomato bushy stunt virus*	Tomato Pith Necrosis - *Pseudomonas corrugate* Roberts & Scarlett
Tobacco Streak - *Tobacco streak virus*	Bacterial Canker - *Clavibacter michiganensis* pv. *michiganensis*	Bacterial Speck - *Pseudomonas syringae* pv. *tomato*	Bacterial Spot - *Xanthomonas campestris* pv. *vesicatoria* (ex Doidge) Vauterin et al.

Common diseases of Peppers in Western United States

Table 2.5 Common diseases of Peppers (Pernezny et al. 2003, Basler and Lang 2012).

Alfalfa Mosaic Virus - *Alfalfa mosain virus* (AMV)	Bacterial Spot - *Xanthomonas campestris* pv. *vesicatoria*	Curly Top Virus - *Beet curly top geminivirus* (BCTV)
Cucumber Mosaic - *Cucumber mosaic cucumovirus* (CMV)	Impatiens Necrotic Spot - *Impatiens necrotic spot virus* (INSV)	Root and Crown Rot - *Phytophthora capsici* (ex Doidge) Vauterin et al.
Potyvirus Mosaic Diseases - *Pepper mottle potyvirus* (PepMoV) - *Tobacco etch potyvirus* (TEV) - *Potato Y potyvirus* (PVY)	Powdery Mildew - *Leveillula taurica* (Lév.) G. Arnaud	Tomato Spotted Wilt - *Tomato spotted wilt virus* (TSWV)
Tobamonvirus Diseases - *Tobacco mosaic virus*	Damping-Off - *Pythium* spp.	Verticillium Wilt - *Verticillium dahliae* Kleb.

Common diseases of Cucurbits in Western United States

Table 2.6 Disease of cucurbits (Zitter et al. 1996, Basler et al. 2013).

Angular Leaf Spot - *Pseudomonas syringae* pv. *lachrymans* (Smith and Bryan) Young et al.	Anthracnose - *Colletotrichum lagenarium* (Pass.) Ellis & Halst	Bacterial Fruit Blotch - *Acidovorax avenae* subsp. *citrulli* (Schaad et al.)	Charcoal Rot - *Macrophomina phaseolina* (Tassi) Goidanich	Downy Mildew - *Pseudoperonospora cubensis* (Berk. & M.A. Curtis) Rostovzev	Fusarium Crown & Foot Rot - *Fusarium solani* f. sp. *cucurbitae* W.C. Snyder & H.N. Hans	Fusarium Wilt - *Fusarium oxysporum* f. sp. *melonis* (Leach & Currence) W.C. Snyder & H.N. Hans
Measles - abiotic disorder	Fruit Rot - *Phytophthora capsici* Leonian	Powdery Mildew - *Sphaerotheca fuliginea* (Schlectend.:Fr.) Pollacci - *Erysiphe cichoracearum* DC	Damping-Off - *Pythium* spp. - *Phytophthora* spp. - *Rhizoctonia solani* - *Acremonium* spp.	Sudden Wilt - *Rhizopycnis vagum* - *Acremonium cucurbitacearum* - *Pythium* spp.	Crown Blight - *Monosporascus cannonballus*	Yellows - Molybdenum deficiency
Cucumber Mosaic - *Cucumber mosaic virus* (CMV)	Cucurbit Aphid-Borne Yellows - *Cucumber aphid-borne yellows luteovirus* (CABYV)	Cucurbit Yellow Stunting Disorder - *Cucurbit yellow stunting disorder* (CYSDV)	Curly Top - *Beet curly top virus* (BCTV)	Potyviruses - *Watermelon mosaic virus* (WMV) - *Zucchini yellow mosaic virus* (ZYMV) -	Squash Mosaic - *Squash mosaic virus*	Verticillium Wilt - *Verticillium dahliae* Kleb.

CHAPTER 3

MANAGEMENT OF WESTERN FLOWER THRIPS IN TOMATO AND BELL PEPPER

The Western flower thrips (WFT), *Frankliniella occidentalis* (Pergande) (Thysanoptera: Thripidae), is a significant agricultural insect pest worldwide. WFT is native to the southwestern United States, but it began spreading to other areas of the world in the 1980s (Kirk and Terry 2003). WFT can cause direct damage through feeding and indirect damage through the vectoring of serious viruses to various hosts. The western flower thrips is a significant pest on both tomatoes and bell peppers.

Life Cycle

Thrips exhibit a metamorphosis that is between complete (holometabolous) and gradual (paurometabolous) (Dreistadt et al. 2007). The life cycle of WFT consists of egg, two larval (nymphal) stages, prepupa, pupa, and winged adult stages. In warmer climates like low desert regions of Arizona and California, thrips are able to complete a generation in approximately two to three weeks (Nuessly 2003, Palumbo 2013). WFT tends to prosper in the moderately warm and dry conditions of this region.

The female commonly deposits eggs singly into soft tissues of the flower, stem, developing fruit, or leaves (Nuessly 2003, Sutherland 2006). The eggs hatch in

approximately two to seven days depending on environmental conditions (Palumbo 2013). The wingless larvae tend to be active and move around the plant while feeding. The first two instars actively crawl or jump on the surface of the host as they feed with their rasping-sucking mouthparts (Frank 2009). The first instar is very small and translucent white with a worm-like body shape (Frank 2009). The second instar larvae resemble the adults except for size, lack of wings, and color (Frank 2009, Palumbo 2013). The first two instars are easily distinguished from the other developmental stages by their red eyes (Frank 2009).

The third instar is called the prepupal (propupal) stage and is a non-feeding stage. Prepupae are similar to the first two larval stages in appearance, but they have developed short wing pads (Palumbo 2013). The pupal stage resembles the prepupal stage in appearance except that the wing pads have lengthened (Palumbo 2013). The pupal stage is also a non-feeding stage. Both the prepupal and pupal stages are inactive. The prepupae and pupae are commonly found in secluded locations (Nuessly 2003, Palumbo 2013, Schuster et al. 2014). These locations are typically in the soil or ground litter below the host plant (Nuessly 2003, Palumbo 2013, Schuster et al. 2014).

The adults of the western flower thrips are approximately 0.5-3 mm in length and are long and narrow in shape (Nuessly 2003). Both the adult male and female thrips have two pairs of fully developed wings fringed with long hairs (Nuessly 2003). The males are light yellow in color, but the females can range in color from yellow to dark drown with dark brown splotches on her abdomen (Palumbo 2013).

Adults live for approximately three to four weeks (Palumbo 2013). Females have been observed living up to 45 days (Cloyd 2010, Cloyd 2012). A female WFT can oviposit 150 to 300 eggs in their lifetime (Cloyd 2010, Cloyd 2012). WFT has a haplo-diploid reproduction system (Cloyd 2010). This means that the females develop from fertilized eggs and the males develop from unfertilized eggs. Unmated females are able to produce haploid eggs (unfertilized eggs) that develop into males (Cloyd 2010, Palumbo 2013).

Crop Damage Caused by Western Flower Thrips

As mentioned previously WFT causes damage to the host plant through feeding behavior. Adults and feeding immatures have rasping-sucking mouthparts (Schuster et al. 2014). The asymmetrical mouthparts have one functional and one non-functional mandible (Sutherland 2006). Feeding damage is caused when WFT uses the functional mandible to slash or tear the plant tissue. The insect then sucks up the plant sap that oozes from the newly formed wound (Sutherland 2006).

WFT has a wide range of hosts, and damage symptoms can vary by host. However, there are a few symptoms that are common among hosts. A “silvery” appearance, called stippling, occurs on the leaves heavily fed on by WFT (Cloyd 2012). This characteristic symptom is caused by the influx of air into the feeding area after the plant fluids have been removed (Cloyd 2012). Another, common sign of thrips infestation is the accumulation of black fecal deposits near or around sights of feeding (Cloyd 2012).

Thrips adults and immatures are gregarious, so as population densities increase, females begin feeding on pollen to gain additional nutrients for reproduction (Cloyd 2010). The gregarious behavior and additional feeding activity by the first two instars can make the injury caused by feeding un-proportional to the insect's size.

The direct damage from feeding can cause yield reductions and aesthetic damage, but at times the indirect damage of vectoring viruses belonging to the genus *Tospovirus* (Family: Bunyaviridae) can be more devastating. WFT is the most important vector of *Tomato spotted wilt virus* (TSWV) and *Impatiens necrotic spot virus* (INSV) throughout the world (Reitz and Funderburk 2012).

Immature WFT can become infected with viruses after feeding on infected plants. The transfer of the virus from the infected plant to the developing thrips can take as little as 30 minutes (Frank 2009). The virus is able to replicate in the insect and persist through the thrips developmental stages. Once infected with the virus, the thrips can vector the virus for life (Frank 2009). It takes approximately 5 to 15 minutes of feeding for a viruliferous thrips to transfer the virus to a new host plant (Frank 2009). Adult WFT are unable to become infected with plant viruses. However, if infected as immatures the mobile adults are capable of causing the spread of the viral disease (Riley and Pappu 2004).

Feeding by WFT on tomato flowers parts can cause bloom abscission and deformed fruit (Schuster et al. 2014). Small pits may develop on the blossom end of fruits if oviposition occurred early in the fruits development (Schuster et al. 2014). Oviposition can also cause subepidermal white spots that may enlarge and eventually develop a halo

as the fruit develops (Schuster et al. 2014). In addition to feeding damage, WFT can vector devastating viruses like TSWV to tomatoes through feeding.

In pepper fields, thrips infestations typically begin close to the edge of the field border. When flower feeding occurs, damage may be present as scars or sunken areas on the stigmatic surface, style, and anthers (Nuessly 2003). If feeding injury occurs to the flower before pollen dehiscence, fruit set can be reduced and deformed fruit may develop (Nuessly 2003). Oviposition and feeding on developing fruit cause deformed calyx and surface scarring that enlarges as development continues (Nuessly 2003). In addition to feeding damage as mentioned previously, WFT vectors devastating viruses to peppers through feeding.

TSWV is a serious threat to pepper production in the United States and Mexico (Crosby 2008). This virus can also become an issue for greenhouse and field grown tomatoes. The symptoms commonly associated with TSWV include bronzing of the leaves, drooping of infected plants, necrotic spots on the leaves, and pale yellow rings on the developing fruit's surface (Basler and Lang 2012, Jones et al. 2014).

Management

There are multiple factors that make WFT difficult to manage in cropping systems and understanding these factors are important to management of WFT. The species is able to reproduce on a wide variety of hosts. WFT also exhibits a short generation time and high fecundity, resulting in overlapping generations in a single cropping season. WFT also demonstrates thigmotactic behavior (Cloyd 2010, Reitz and Funderburk 2012),

and thus, the insect needs to be in close contact with its surrounding surfaces. Therefore, thrips are typically found in secluded parts of the host plant enabling them to evade direct exposure to many foliar insecticides.

Due to WFT's pest status and its ability to vector destructive viruses, management has required intensive use of insecticides in both agricultural and horticultural settings. Horticulture's low aesthetic thresholds have also provided the conditions in which insecticidal chemicals are often over used. Over use and intensive use of a select few chemistries places a greater selection pressure on a pest population for resistance.

In addition to the artificial selection pressure placed on *Frankliniella occidentalis*, the insects' polyphagous feeding behavior has allowed it to develop multiple enzymatic detoxification pathways to cope with host plant defenses (Reitz and Funderburk 2012). Due to the selection pressure placed on WFT by both natural and human means the insect has developed resistance to numerous insecticide classes worldwide including organochlorines, pyrethroids, carbamates, organophosphates and spinosyns (Bielza 2008, Reitz and Funderburk 2012). There is still a heavy reliance on synthetic insecticides to control WFT in vegetable crop production throughout the world. The continued reduction in efficacy of available products to control WFT has helped to spark the need for more integrated approaches and products with diverse modes of action.

Cultural Management Strategies

There are several cultural practices that can reduce the possibility of a WFT outbreak. It is advised to avoid planting peppers or tomatoes next to onions, garlic, or

greenhouses where ornamentals (e.g. cut flowers) are being grown because WFT is able to develop large populations on these crops (Basler and Lang 2012). Researchers at the University of Florida have demonstrated that the use of Ultraviolet light (UV)-reflecting mulches can deter adult thrips from migrating into production fields (Nordlie 2012, Basler and Lang 2012). These UV-reflective mulches disrupt the visual cues in specific UV spectrums used by thrips to identify suitable host. A study conducted by Reitz et al. (2003), showed that UV-reflective mulch significantly reduced adult thrips populations early in the season for peppers when compared to the standard black mulch. In a similar study conducted by Momol et al. (2004) in tomatoes, the repellant benefits of UV-reflective mulch were reduced by the end of May, as this is when the plants were large enough to cover the mulch. However, the early reduction in immigration of adult thrips significantly reduced the incidence of TSWV with or without insecticide treatment (Momol et al. 2004).

In addition to having reflective mulch in the field under the crop, producers can plant trap crops like sunflowers that lack the reflective mulch (Nordlie 2012). Without the UV-reflective mulch, thrips will be able to use visual cues to locate these trap crops on the edge of fields. Producers can then use insecticides to control the pest population in these trap crops and reduce immigration into the crop. It is also highly advised that producers place yellow and blue sticky traps in the field to monitor the population levels of thrips in their fields. By monitoring and scouting fields producers can select the appropriate time to apply management tactics.

Conventional Products

According to the Insecticide Resistance Action Committee (IRAC), WFT has been reported to be resistant to carbamates (Group 1A – IRAC), organophosphates (Group 1B – IRAC), cyclodiene organochlorines (Group – 2A), phenylpyrazoles (Group 2B – IRAC), pyrethroids (Group 3A – IRAC), neonicotinoids (Group 4A – IRAC), spinosyns (Group 5 – IRAC), and avermectins (Group 6 – IRAC)(Salgado et al. 2014). Although, WFT has shown the ability to develop resistance to multiple chemistries, these products are still recommended and used. The University of California IPM pest management guideline for peppers recommends using imidacloprid (Admire Pro®), spinetoram (Radiant® SC), and flonicamid (Beleaf® 50SG)(Basler and Lang 2012). These products fall under different modes of action and should be rotated to help manage resistance.

With the amount of diverse chemistries that WFT has developed resistance, Insecticide Resistance Management (IRM) is of great importance when selecting management strategies to control this pest in or around crops. IRM includes the use of insecticide rotation schemes, economic thresholds, and cultural practices (Gao et al. 2012). Economic thresholds have been established for fruiting vegetables, including pepper and tomato for WFT and it has been demonstrated that pepper can tolerate a larger pest load (Gao et al. 2012, Reitz and Funderburk 2012). Natural enemies can also play an important role in managing WFT; however, their populations can be disturbed by improper selection and timing of insecticide treatments (Gao et al. 2012). Alternative products like biopesticides that have less of an effect on natural enemies, can play a vital role in IRM of WFT.

Biopesticide Products

Due to the continued development of resistance, scientists have been developing potential biopesticides to help producers in their resistance management strategies. These biologicals have included microbial organisms (e.g. bacteria, fungi) and plant derived (botanicals) products (Copping and Menn 2000).

There are only a few bioinsecticides currently available for commercial use in vegetable production. As more companies begin to expand their biological divisions more products may become available to producers. A few of these products will be Organic Materials Review Institute (OMRI) registered. Some products will not be OMRI registered because of the additional cost to register.

The soil bacterium, *Saccharopolyspora spinosa* Mertz & Yoa, was originally isolated from a rum still in the Caribbean, and it has been developed into multiple commercial products in the United States (Copping and Menn 2000). Spinosyns are metabolites that are derived from the fermentation of the bacterium (Reitz and Funderburk 2012). Dow AgroSciences researchers developed spinosad, a commercial product that is a mixture of spinosyn A and spinosyn D (Copping and Menn 2000). These metabolites have a novel mode of action known as the nicotinic acetylcholine receptor (nAChR) allosteric activators (Group 5 – Insect Resistance Action Committee (IRAC))(Salgado et al. 2014). The novel mode of action allows products with this type of active ingredient to be used in rotation with neonicotinoids. Spinosad is available as a water-based suspension concentrate (SC) formulation in commercial products under the

trade names Tracer®, Conserve®, Success®, SpinTor®, and Entrust® (Dow AgroSciences) (Copping and Menn 2000). Tracer® is only registered for field crops (e.g. corn). Entrust® is the only spinosad product that is OMRI listed.

A study conducted by Jones et al. 2005, showed in laboratory bioassays that spinosad was toxic to both immature and adult thrips either as a direct or residual contact application. Spinosad provided mortality of >90% within 48h of treatment for laboratory bioassays on both larval and adult WFT (Jones et al. 2005). In greenhouse bioassays, spinosad residues were able to provide a mortality of 96% up to 28 days after application (Jones et al. 2005). In greenhouses, spinosad residues have caused significant mortality up to 57 days after application (Jones et al. 2005). However, spinosad quickly undergoes photodegradation in field settings, and prolonged residual activity is uncommon.

Unfortunately, due to a lack of alternatives and the effectiveness of spinosyns on WFT, producers have placed a heavy reliance on the compound to control the pest. This increased selection pressure has resulted in the development of resistance to the metabolite. Resistance to spinosyns was first observed in Australia in 2002 and later reported in the United States in 2009 (Herron and James 2005, Weiss et al. 2009). In an effort to manage resistance and broaden the spectrum of insecticides available to manage WFT, other biological, botanical, and adaptations of existing chemistries have gained interest (Reitz and Funderburk 2012).

Entomopathogenic fungi are being developed and tested for their potential as crop protectants. There are approximately 750 fungal species known to infect insects, but only a few have been developed or examined for commercial crop protection (Copping and

Menn 2000). Two mycoinsecticides that are currently available that show good efficacy in lab trials are *Metarhizium anisopliae* (Metsch) Sorokin and *Beauveria bassiana* (Balsamo) Vuillemin (Copping and Menn 2000, Niassy et al. 2012). A third mycoinsecticide, *Verticillium lecanii* (Zimm.) Viégas, that was developed to control whitefly, but shows some activity on WFT.

Metarhizium anisopliae strain F52 is a commercially available mycoinsecticide under the trade name Met52® (Novozymes). This product is registered for use on multiple vegetable crops for the management of thrips, whiteflies, and mites. The product can be applied as a soil drench, foliar application or root dip for transplants. The entomopathogenic fungus spores work differently than other microbials that need to be ingested. These fungi attack the insect host by actively penetrating through openings in the cuticle (Copping and Menn 2000). *M. anisopliae* is very effective at killing target insects when applied foliarly. The fungus penetrates the cuticle and invades the hemolymph, causing death in 7-10 days (Copping and Menn 2000, Niassy et al. 2012). The infected insect remains on the host plant during infection. After the insects' death, spores are released keeping the level of infective material high (Copping and Menn 2000).

Beauveria bassiana is another commercially available mycoinsecticide. The fungus is available under the trade names Naturalis-L®, Naturalis-O® (Troy), BotaniGard®, and Mycotrol® (Mycotech)(Copping and Menn 2000). Mycotrol® is the only product that is OMRI listed. This fungus invades the insect host body and at the end of development produces conidia that will become attached to the outside of the cuticle and further spread the infection (Copping and Menn 2000). The insect typically remains

alive for 3-5 days after infection. Free water and high levels of humidity are required for the germination of the conidia and subsequent infection.

Verticillium lecanii is not commercially available in the United States, but it is used in the European Union (EU) under the trade name Mycotal® (Koppert)(Adlam 2012). Similar to many of the other microbial biopesticides, *V. lecanii* can be very effective in a specific temperature and relative humidity range. For the fungal pathogen to remain virulent against WFT the temperature must be in the range of 18-28°C (64-82°F) with a relative humidity of 70% for several days after application(Adlam 2012). These specific environmental conditions do not always occur when the pest pressure is present in the crop. Therefore, it is not likely to be used as a stand-alone product, but it may work as an alternative or in a rotation

Summary

Developing and implementing both Integrated Pest Management (IPM) strategies and Insecticide Resistance Management (IRM) strategies takes a holistic approach to controlling pests like the Western Flower Thrips. This holistic approach requires producers to understand the life cycles and disease cycles of the pest and biological control agents (i.e. natural enemies, microbial biopesticides) used to manage the pest population. By understanding these cycles, a producer can better select products, whether they be conventional or alternative (i.e. biopesticides), that won't disturb the natural cycle that is occurring in their fields. Biopesticides are products that can provide producers

opportunities to rotate chemistries and reduce the disruption to the beneficial organisms in their fields that may help them to combat pest issues.

From my experience at RD4AG testing new agricultural products for pest management in tomatoes and peppers, I saw the benefit of having multiple options for controlling pests. In the contracted studies conducted at RD4AG on WFT in tomatoes and peppers, differences were observed when these new alternatives (i.e. biopesticides) when tested against commercial standards (i.e. synthetic insecticides). Majority of the test products were in the developmental stage and when compared to commercial standards they showed little to no improvement in efficacy over the currently available products.

However, these products did provide additional benefits when compared to the commercial standards. Some of the benefits provided included worker safety, reduced residue levels, and reduced pre-harvest interval (PHI). The reduced PHI allowed the biopesticide products to be applied right up to the day of harvest.

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CHAPTER 4

MANAGEMENT OF POWDERY MILDEW IN CANTALOUPE AND BELL PEPPER

Powdery mildew has been a concern for crop producers for many years. The disease is caused by a number of fungi belonging to different genera including *Sphaerotheca, Uncinula, Microsphaera, Phyllactinia, Erysiphe, Podosphaera,* and *Leveillula* (Olsen 2011). Powdery mildew affects a wide range of hosts (e.g., vegetables, fruit trees, grapes, native annuals); however, the pathogens associated with the disease are typically host specific or only infect plants in the same plant family (Olsen 2011).

Powdery mildew can be a serious disease for cantaloupe and pepper producers in arid and semi-arid growing regions of the United States. The pathogens associated with the disease prefer warm temperatures, moderate relative humidity, low light intensity, and reduced airflow (Henderson 2009, Olsen 2011). Higher relative humidity is not common in low desert valleys; however, microclimates with environmental conditions that favor powdery mildew development are consistently produced within dense foliage in irrigated crops (Henderson 2009).

Although several different fungal species cause powdery mildew, the symptoms are typically similar across hosts. All of the species associated with the disease are

obligate parasites, and scientists are unable to culture them in the laboratory. These fungi are typically epiphytic with mycelium growth occurring on the leaf surface of the infected host plant (Yarwood 1957). However, there are differences in the disease cycles between the pathogens.

Cantaloupe

Powdery mildew occurs annually on melons in the low desert valleys of California and Arizona. It typically occurs in early to mid summer. The disease can be caused by two separate fungal pathogens, *Erysiphe cichoracearum* DC ex Merat (syn. *Golovinomyces cichoracearum*) and *Sphaerotheca fuliginea* (Schlechtend: Fr.) Pollacci (syn. *Podosphaera xanthii*) (McGrath and Thomas 1996, Kuzuya et al. 2003, Basler et al. 2013). *E.cichoracearum* is rare, but *S. fuliginea* is commonly associated with causing powdery mildew in cantaloupe (*Cucumis melo* L.) (Basler et al. 2013). Three races, race 1, 2 US and S, of *S. fuliginea* (syn. *P. xanthii*) have been identified in the region (Henderson 2009).

Powdery mildew colonization, sporulation, and dispersal are all favored by the dry conditions that are commonly observed in low desert valleys. Disease development for *S. fuliginea* is optimum at a temperature range of 20-27°C (68-81°F)(McGrath and Thomas 1996). The spores (conidia) of *S. fuliginea* can cause infection in a temperature range of 10-32°C (50-90°F)(McGrath and Thomas 1996). Under favorable conditions the disease cycle for powdery mildew can take as little as 4 to 5 days (Matheron and Porchas 2004b)

The initial infection is introduced into the field by wind-dispersed conidia that developed on alternate hosts. At the beginning of the infection, *S. fuliginea* appears as small white spots on the surface of leaves and stems. As the disease progresses the spots develop into pale yellow lesions that will eventually be covered in fluffy white mycelium (Basler et al. 2013). The mycelium growth is only superficial and the fungus must develop specialized structures called appressoria to remain attached to the host (Yarwood 1957). Initially the fungal growth is only on the abaxial surface of older and shaded lower canopy leaves (McGrath and Thomas 1996).

S. fuliginea lacks endophytic growth and, as such, must develop specialized cells called haustoria to gain nutrients from the host plant (Henderson 2009). These specialized cells are derived from the appressoria and are globular shaped, uninucleate cells (Yarwood 1957). The haustorium never penetrates the host cell and is always surrounded by host-plasmalemma (Yarwood 1957).

After adequate colonization and development has occurred by the fungus, asexual reproduction will occur through the production of conidiophores. Conidiophores are specialized hyphal structures that develop asexual spores called conidia (Yarwood 1957). The conidia will then develop when there is an absence of free water on the leaves' surface (Henderson 2009).

Powdery mildew may occur during the spring production season, but it is more common during the fall production season for melons since the environmental conditions are closer to being optimal. The disease initially starts as small chlorotic spots on the stems (vines), petioles, and leaves (Basler et al. 2013). The older and shaded leaves are

often the first to show symptoms. As the disease progresses the chlorotic spots enlarge and become covered with fluffy whitish mycelium growth (McGrath and Thomas 1996, Basler et al. 2013). The powdery appearance will generally be observed on the abaxial side of the leaf surface. Severely infected leaves become entirely chlorotic and exhibit signs of wilting in the heat of the afternoon (Basler et al. 2013). These leaves eventually become dry, brown and papery (Basler et al. 2013).

As the leaves dry up and senesce, the plant will become defoliated. The loss in foliage increases the direct exposure of developing fruits to the sun. This fruit can become sunburned and will be inferior in quality (Bruscia et al. 1963). These inferior fruit will typically be reduced in size and have lower sugar content or (Brix, °Bx)(Kemble 1996). Degrees Brix is a way of measuring the sugar content of an aqueous solution. One degree is equal to 1 gram of sugar in 100 grams of solution.

Bell Pepper

Powdery mildew can also be a serious disease for pepper producers in the warm low desert valleys of Arizona, New Mexico, and California. Severe infections often lead to defoliation and high crop losses. The causal agent of the disease powdery mildew in bell (sweet) peppers (*Capsicum annuum* var. *annuum* L.) is *Leveillula taurica* (Lév.) G. Arnaud, which is the teleomorph of *Oidiopsis sicula* Scalia (syn. *O. taurica* E.S. Salmon)(Goldberg 2003, Basler and Lang 2012).

L. taurica differs from powdery mildew pathogens in other genera like the ectoparasitic pathogen associated with powdery mildew on cantaloupe because part of the fungus' life cycle occurs endophytically (Goldberg 2003, Basler and Lang 2012). The fungus does exhibit epiphytic growth, but only for the short time that the germ tube is seeking stomata to cause infection (Elad et al. 2007).

Powdery mildew can occur on peppers in a dry or humid climate because the conidia of *L. taurica* can germinate and develop a germ tube under any level of relative humidity (RH) from 0-100% if temperatures are between 18-33°C (64-91°F) (Goldberg 2003, Basler and Lang 2012). This wide humidity range is possible because conidia of *L. taurica* contain sufficient water to germinate and initiate growth (Smith et al. 1999). Temperatures above 35°C (95°F) suppresses development of the fungal pathogen (Basler and Lang 2012). The temperature range required by *L. taurica* conidia to germinate is commonly observed during the morning and evening in agricultural fields of the low desert. However, it is also typical of the low desert to have temperatures above 35°C (95°F) during the day when bell peppers are being grown in the field.

Leveillula taurica (*O. sicula*) is reported to have a host range of over 700 plant species in 59 different families (Goldberg 2003). This wide range of hosts include important crops like alfalfa (*Medicago sativa* L.), cotton (*Gossypium hirsutum* L. and *Gossypium barbadense* L.), artichoke (*Cynara scolymus* L.), and onion (*Allium cepa* L.)(Goldberg 2003). All of these crops are grown in rotation or in close proximity to pepper fields in the low desert valleys of the southwest United States. The fungus also infects some ornamental trees, e.g. Chilean mesquite (*Prosopis chilensis* (Molina)

Stuntz), a common landscape tree in southern Arizona (Goldberg 2003). The native honey mesquite (*Prosopis glandulosa* Torr.) can also become infected and serve as a source of inoculum (Goldberg 2003).

Because of its wide range of hosts in the desert lowlands, the obligate fungus is able to survive and reproduce. The asexual spores (conidia) are wind dispersed and typically cause the initial infection in peppers. After germination, the conidia develop a germ tube that continues to grow on the surface of the leaf until it encounters a stomate (Elad et al. 2007). Then the mycelium growth penetrates the host plant through the opening and begins to grow into the mesophyll by intercellular growth (Palti 1988). These infection hyphae continue growth into the spongy parenchyma cells, and they have been observed growing in the palisade parenchyma cells (Palti 1988). Once colonization has occurred, the pathogen develops haustoria within the infected parenchyma cells that absorb nutrients from the host (Palti 1988). The fungus then produces conidiophores that emerge back out of stomatal openings (Goldberg 2003). These conidia are typically seen on the underside (abaxial) of the leaf, but can be observed on the adaxial side under the right conditions. Conidia are then dispersed and spread to other suitable hosts. The cleistothecia (sexual spores) are developed by the teleomorph (perfect stage) and are rarely observed developing on cultivated pepper plants (Goldberg 2003, Basler and Lang 2012). Cleistothecia have been observed developing on alternative hosts, but typically are not the infecting life stage of *Leveillula taurica* (*O. sicula)* for peppers.

The incidence of powdery mildew is higher in more humid conditions; however, the disease and resulting defoliation is more severe in dry conditions (Goldberg 2003).

The need for irrigation in low desert vegetable production creates a unique mixture of these two extremes within an individual field level. Powdery mildew incidence is lower in sprinkler-irrigated fields versus furrow or drip-irrigated fields (Goldberg 2003). The water droplets from the sprinkler irrigation can potentially wash the conidia off of the host plant, preventing infection. In additional to being washed off, the water content in the conidia makes them vulnerable to bursting when free water is present (Smith et al. 1999).

As with most powdery mildews, the most noticeable symptom to the naked eye is the white, powdery growth seen on the abaxial side of an infected leaf. In peppers, pale green to yellow lesions with necrotic centers may form on the adaxial side of the leaf (Goldberg 2003, Elad et al. 2007). Leaves showing lesions may eventually turn entirely chlorotic or brown (Goldberg 2003). Symptoms develop first on older leaves, and as the infection increases, these leaves will drop prematurely (Elad et al. 2007, Basler and Lang 2012). As these leaves drop, the developing fruit is exposed to direct sunlight, and they become sunburned and unmarketable. In severe infections when defoliation is high, yield losses to sunburned fruit can range from 50-60% (Smith et al. 1999).

Management

The management of powdery mildew on cantaloupe is slightly easier than on bell peppers. This is because part of the disease cycle of *Leveillula taurica* (*O. sicula*) on peppers is endophytic. The stages of the fungus that grow inside the host plant tissue are protected from foliar fungicides. However, products that have systemic activity can be

effective at controlling powdery mildew on peppers. Because powdery mildews typically grow epiphytically they can be controlled with foliar applied fungicides if applied at the appropriate time.

Cultural Management Strategies

The cultural practices that help reduce the disease incidence from powdery mildew in cantaloupe and bell pepper are similar. A producer can start by choosing resistant varieties over susceptible varieties. It is also important to have good sanitation in and around the field, by controlling alternate hosts (e.g. weeds) both in and outside the cultivated area (Basler and Lang 2012, Basler et al. 2013). Sanitation will only slightly reduce the potential inoculum load because *L. taurica* has such a large host range, and it can be dispersed long distances by wind (Basler and Lang 2012).

Because cultural practices will only reduce the potential of disease, it is extremely important that growers monitor their fields for powdery mildew on a regular basis. Monitoring for disease presence should begin early during the vegetative growth stage of the plant when warm weather is just beginning and continue on through the end of the cropping season to prevent late season yield loses (Basler and Lang 2012, Basler et al. 2013). Fields planted to resistant varieties should be continually monitored as some races of powdery mildew have broken host plant resistance (Basler et al. 2013). Close monitoring and scouting of fields provide the opportunity to apply control measures at an early development stage of the disease when applications will be most effective.

As with management of most plant diseases the earlier in development the control product is applied the more effective the product will be at controlling the disease. It is recommended to have fungicidal protection in place before environmental conditions become suitable for disease development (Matheron and Porchas 2005). This typically means that an application needs to occur early in the vegetative growth stage to prevent loss of foliage. Preventative applications are recommended, as fungicides are not effective at curing established disease (McGrath 2012).

Conventional Products

Powdery mildew is primarily managed with fungicide applications to prevent damage and economic loss. For melons multiple applications may need to be applied as symptoms reappear (Basler et al. 2013). If multiple applications are to be made it is highly recommended to alternate products with different modes of action, especially if the products being applied have a medium to high resistance potential (Basler et al. 2013). In addition to rotating chemistries, fungicides with different Fungicide Resistance Action Committee (FRAC) codes may be tank mixed to reduce the potential of resistance developing. FRAC releases periodic updates on plant pathogens that have a high potential for developing resistance and on fungicides that are also at increased risk.

Multiple commercial fungicides are available for managing powdery mildew in pepper and melons. Many of these commercial products are labeled for use in both cucurbits (melons) and peppers. Some of the commercial products that are labeled for both crops include Quadris® (azoxystrobin – FRAC Group 11), Cabrio® (pyraclostrobin –

FRAC Group 11), Rally® (mycolbutanil – FRAC Group 3), Quintec® (quinoxyfen – FRAC Group 13), and Flint® (trifloxystrobin FRAC Group 11) (Basler and Lang 2012, Basler et al. 2013). Procure® (triflumizole – FRAC Group 3) is an additional commercial product labeled for use in cucurbits (Basler et al. 2013). An efficacy trial run in Yuma, AZ in 2008 and 2009 showed that Quintec® and Procure® when applied alone provided 98 to 100% control of powdery mildew on cantaloupe when compared to untreated controls (Matheron and Porchas 2013). The same trial showed that the best treatment strategy was to apply Quintec® followed by Microthiol® then Procure® and a final application of Microthiol® if required (Matheron and Porchas 2013). The active ingredient in Microthiol® is wettable sulfur (FRAC group M2) (Basler et al. 2013, Matheron and Porchas 2013). This treatment strategy provided 100% control throughout the growing season when compared to untreated checks.

From the list of commercial products provided in this document and data showing the effects of rotating chemistries, one can see that rotation of products is important for disease resistance management. However, there are only a few modes of action available to manage powdery mildew in cantaloupe and bell peppers. Biopesticides can help alleviate selection pressure placed on powdery mildew pathogens when used in rotations with conventional chemistries. The rotational treatment provided earlier that includes Microthiol is a good example of the benefit of adding a biopesticide to the chemical rotation.

Biopesticide Products

There are several different biopesticides available commercially that have proven to be effective against powdery mildew in cantaloupe and bell pepper. The majority of these biopesticides are included in the categories of oil (mineral and botanical), copper, potassium bicarbonate, sulfur, and biofungicides (microbials) (McGrath 2001). Some materials or products are listed with the Organic Materials Review Institute (OMRI) and classified as organic disease management products (Matheron and Porchas 2013).

Some of the available biopesticide products used to control powdery mildew will work for bell peppers, but not cantaloupe and vice versa. Sulfur can be used to control powdery mildew on peppers, but is not recommended for control in cantaloupe in the desert low lands (McGrath 2001, Matheron and Porchas 2004a). The environmental conditions (i.e. high temperatures) that favor powdery mildew in the low desert valleys can cause the compound to severely burn the leaves of many melon varieties (Matheron and Porchas 2004a). Sulfur is included in the FRAC group M2 (multi-site contact), and it is recommended that application not occur within two weeks of an oil application as this could cause additional burning of the foliage (Basler and Lang 2012, Fungicide Resistance Action Committee 2013). The commercial sulfur product labeled for use in cantaloupe is Microthiol® and in peppers is Sulfur DF (Basler and Lang 2012, Basler et al. 2013).

Another, inorganic product that can be used to manage powdery mildew in cantaloupe and bell peppers is potassium bicarbonate ($KHCO_3$). Potassium bicarbonate is the active ingredient in Kaligreen® and Milstop® (McGrath 2012). Both of these

products are OMRI listed, and they can be used in organic vegetable production. A study done by Fallik et al. (1997) showed that potassium bicarbonate reduced disease severity to 10% or less. The reduction in disease severity provided by potassium bicarbonate resulted in significant reduction in leaf defoliation and sun scalded fruit when compared to untreated and penconazole treated plants (Fallik et al. 1997).

There are a few botanical products available commercially that are labeled as fungicides. A few of these products include Mildew Cure™, Organocide®, Sporatec AG ™, and Trilogy™ (McGrath 2012). Many of these products are mixtures of oils and plant extracts. For example, Sporatec AG ™ is labeled for control of powdery mildew in melons, and it is also OMRI listed. Sporatec AG ™ is a mixture of rosemary oil, clove oil, and thyme oil (McGrath 2012). Another, product mixture is Organocide® which contains sesame oil and fish oil (McGrath 2005). Organocide® was shown to be as effect at controlling powdery mildew on cucurbits as Microthiol® in a study conducted in 2005 (McGrath 2005). However, these products typically have a lower efficacy, but could be used in rotation when disease pressure is low.

To add to the diversity of biopesticides available to control powdery mildew there are also several microbial species that have been developed into commercial products. Two of the more well known products are Actinovate AG® (*Streptomyces lydicus*)(FRAC Group – NC) and Serenade® or Serenade Max® (*Bacillus subtilis*)(FRAC Group – 44) (Matheron and Porchas 2013). These products were tested in the Yuma area in 2008 and 2009, but they were shown to have little effect on the disease when used as the sole treatment for the growing season (Matheron and Porchas 2013). When used as the sole

treatment for the season, Serenade Max® out performed Actinovate AG® with maximum average disease control of 35.8% and 29.2%, respectively (Matheron and Porchas 2013). Serenade Max® showed better potential when used in rotation with Procure® and Quintec®.

Summary

Can biopesticides be an additional management component for producers of specialty vegetable crops? Although, some biopesticide products show a reduced efficacy when compared to synthetic chemicals they can help alleviate selection pressure being placed on crop pests by continual use of a small number of chemical classes. This reduction in selection pressure can come from adding biopesticides to the management rotation. By advocating the use of biopesticides in a chemical rotation scheme during a growing season, producers can be educated in establishing a better resistance management and IPM strategy for their particular crops needs.

Biopesticides being used in product rotations for conventional farmers is not the major use for these products. Biopesticide products that are listed as OMRI can be used by certified organic farmers to protect valuable crops that may otherwise be subject to pest outbreaks. Certified organic farmers typically use IPM strategies to manage pest and having an additional tool like a biopesticide can be very beneficial. Biopesticide products can allow the production of organic produce to occur on a larger scale.

In order for biopesticides to become stand-alone products in the future, some work needs to be done. Many of the biopesticides that have microbials (i.e. bacteria, fungi) as active ingredients have a narrow range of environmental conditions that they are active and can be effective. These products would benefit from studies conducted to determine if this range of environmental conditions could be modified. In addition, it would be beneficial to evaluate the ability of these products to be tank mixed with other products. Tank mixing can provide another method of managing resistance development.

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