PESTICIDE SUSCEPTIBILITY OF POTATO TUBERWORM IN THE PACIFIC NORTHWEST

By

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accomplishment, I could not have completed this without you. I love you and look forward to spending the rest of our lives together.

PESTICIDE SUSCEPTIBILITY OF POTATO TUBERWORM IN THE PACIFIC NORTHWEST

Abstract

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The purpose of this study was to determine the baseline susceptibility of potato tuberworm, *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae), in the Pacific Northwest to insecticide exposure. Potato tuberworm (PTW) is a major economic pest in all major potato production areas of the world. Control through the use of insecticides is an effective, inexpensive, and therefore popular pest management method utilized by growers. In this study, the lethal concentrations and lethal times (LC and LT, respectively) were determined using potato leaf bioassays. The LC studies evaluated mortality levels after subjecting the neonate larvae to a range of concentrations of the insecticides methamidophos (Monitor), indoxacarb (Avaunt), spinetoram (Delegate), and esfenvalerate (Asana). Bioassays were evaluated at three and 24 hours after larvae were placed on treated leaf disk surfaces. The dose-response results for each insecticide were transformed to units of mass active ingredient (a.i.) per acre so that bioactivity could be compared to recommended product label application rates. LC_{50} values of 29.2×10^{-3} lb a.i./acre and 23.1×10^{-3} lb a.i./acre were estimated using probit analysis for 3- and 24-h

exposures, respectively, of PTW larvae to methamidophos on treated leaf disks. PTW larvae responded to 3- and 24-h exposures of indoxacarb with estimated LC_{50} values of 1.43 x 10^{-3} lb a.i./acre and 0.026 x 10^{-3} lb a.i./acre, respectively. LC_{50} values of 2.84 x 10^{-3} lb a.i./acre and 0.148 x 10^{-3} lb a.i./acre were estimated for 3- and 24-h exposures, respectively, of PTW larvae to spinetoram. LC50 response of PTW larvae to esfenvalerate following 3- and 24-h exposures was estimated to be 0.013 x 10^{-3} lb a.i./acre and 0.006 x 10^{-3} lb a.i./acre, respectively. The LC50 estimates for exposure of PTW larvae to all insecticides ranged from at least one order of magnitude to three orders of magnitude less than product label application rates.

Larval mortality was observed at increasing time intervals of exposure to leaf disks treated with insecticides at rates equivalent to their estimated LC95. Larvae died within two hours after exposure to all insecticides, but onset of lethality varied somewhat among the tested compounds. Time to larval death was slowest for methamidophos exposure with estimated LT_{50} and LT_{95} of 75 min and 146 min, respectively. Indoxacarb results were similar to methamidophos with LT_{50} and LT_{95} values of 53 min and 159 min, respectively. Spinetoram caused mortality much faster than both indoxacarb and methamidophos. The LT_{50} and LT_{95} values were 26 min and 58 min, respectively. PTW larvae died most quickly following esfenvalerate exposures with estimated LT_{50} and LT_{95} values of 11 min and 25 min, respectively. Based on this study, low concentrations of esfenvalerate and spinetoram caused high levels of mortality in the shortest amount of time. Indoxacarb and methamidophos caused sufficient morality but were comparatively

slower acting. To predict the persistence of bioactivity under field conditions, literature-derived half-lives for the four insecticides were used to model decline in mortality based on the dose-response data from the probit analyses. Methamidophos, indoxacarb, and esfenvalerate were predicted to cause 95-100% mortality for about five days after a theoretical application of the maximum recommended product label rate. In contrast, spinetoram associated mortality was predicted to decline to about 80% within two days after application.

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Dedication

To my parents, this degree is a result of your dedication and commitment to me. I can never thank you enough for always believing in me and pushing me to work hard and strive for more.

To my wife Becki, we can finally get back to living. This is as much yours as it is mine. Thanks for trusting in me, I hope I make you proud.

To my sons Braedon and Eli, hard work never goes unnoticed. Never give up on your dreams, and laugh a little along the way.

Introduction and Literature Review

History and Surrounding Area

Potato tuberworm (PTW), *Phthorimaea operculella* (Zeller) (Lepidoptera: Gelechiidae), is a widely distributed insect pest of solanaceous crops in almost all tropical and subtropical regions of the world (Kroschel 1996b), but it is thought to have originated in South America (Picard 1912). PTW has been an established pest on potatoes in the United States, having been recorded in California since 1856. Damage to potato tubers in the field and in storage can be extreme and is unacceptable in U.S. markets. The Columbia Basin of Oregon and Washington have recorded several PTW tuberworm infestations over the last two decades. However, damage was not a major concern for growers in the Pacific Northwest until 2003 (Schreiber et al. 2007).

Early attempts to control tuberworm in the field depended on cultural practices (Langford 1933). Soil moisture, especially applied via irrigation, continues to be the most important cultural practice utilized in the field to prevent tuberworm infestations (Foot 1974a). Control through irrigation is achieved by physical barriers that eliminate soil cracks and spaces through which larvae would crawl deeper into the soil and possibly reach tubers. Other methods of cultural control include planting seed pieces at least 15 cm deep and harvesting crops earlier in the season in regions with cooler planting seasons (Raman and Booth 1983).

Biological control has also been an important mortality factor in regulating PTW populations. Control from parasitoid wasps, such as *Copidosoma* spp. and *Apanteles* spp., reduce field incidence levels of PTW in other parts of the world (Redolfi and

Vargas 1983). Parasitoid wasps have been collected from PTW in the Pacific Northwest, but the significance of these parasitoids in controlling outbreaks is currently unknown (Rondon et al. 2006). The significance of other common predators in the region, such as lady beetles, big-eyed bugs, and ground beetles in controlling potato tuberworm is also unknown (Rondon et al. 2007). The use of bacteria, viruses, and nematodes is being widely studied to offer biological control options for commercial growers (Kroschel 1996a).

Fast and effective control was achieved with the advent of insecticides such as DDT (Helson 1949), with less importance given to biological and cultural practices. However, insecticide applications have not always prevented high levels of tuber infestations (Foot 1974b). California reported PTW resistance to DDT by 1954 (Bacon 1960). In many countries, experience demonstrates that it is unrealistic to rely solely on the use of chemical insecticides to control this pest (Raman and Booth1983), especially because moths rapidly develop resistance.

This study established baseline susceptibility of PTW to several insecticides used in the Columbia Basin of Washington and Oregon. The lethal concentration of each insecticide killing 50% and 95% of a neonate larval test population was determined. Also, those insecticides that kill the fastest are likely to function most efficiently under environmental conditions given the tuberworm propensity to disperse, and the heterogeneous residue distributions in the plant canopy. Therefore, the time needed to kill 50% and 95% (LT) of the larval population using each compound's LC_{95} rate was also determined. The four compounds used in this study, methamidophos, indoxacarb,

spinetoram, and esfenvalerate were chosen because of high frequency of use for PTW in the Pacific Northwest and the world and because of their unique modes of action. The active ingredients tested in the bioassays were dilutions of the commercial product formulations, Monitor, Avaunt, Delegate, and Asana respectively.

Tuberworm Biology

The PTW has four life stages: adult, egg, larva, and pupa. Adult PTW are small gray moths with a wing expanse of 0.5 inch (1.2 cm) (Figure 1; Flint 1986). The forewings of male moths have two to three dots, while female wings possess an "X" pattern (Rondon et al. 2007). Wings are held close to the body when at rest, which gives the moth a slender appearance. The female moths will produce pheromones to attract the male moths for mating purposes. Adult females may begin to lay eggs two to four days after emergence during mid summer conditions (Malakar-Kuenen and Tinsey 2006). A female moth can lay 150 to 200 eggs individually on rough surfaces such as soil (Traynier 1975), potato eyes, or directly on the foliage (Fenemore 1980). Studies show that moths can traverse short distances of 10 cm (4 inches) through soil cracks or burrow through loose soil to deposit eggs on tubers (Rondon et al. 2007).

The white, spherical eggs are less than 0.06 cm (0.02 inch) in diameter (Rondon et al 2007) (Figure 2). The eggs will become more yellow as they mature until hatching, when they become black (Foot 1998). In mid-summer eggs can hatch in two to six days after oviposition (Foot 1998).

Figure 1. Potato tuberworm adult (copied from UC Statewide IPM Program, 2007 University of California, http://www.ipm.ucdavis.edu/PMG/P/I-LP-POPE-AD.012.html).

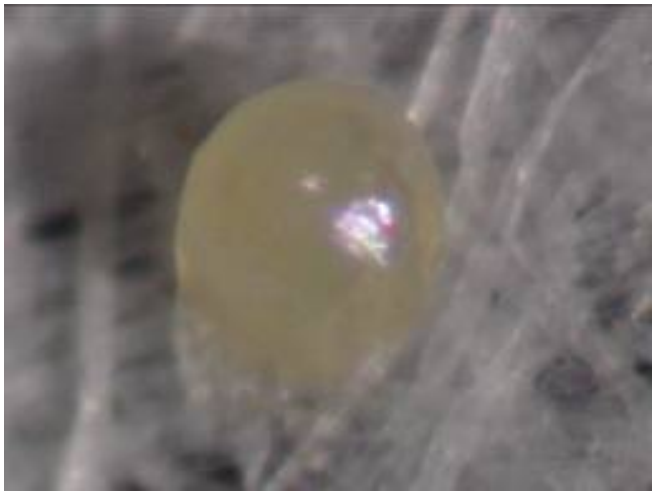

Figure 2. Potato tuberworm egg (**Photo: S. DeBano, Oregon State University, copied from** http://thepgi.com/resources/tuberworm-2007.pdf.

Neonate first instar larvae are 0.01 cm (0.004 inch) in length with a brown head and dark prothoracic shield (Godfrey 2004). Young larvae are grey or yellow-white, while mature larvae vary in color ranging from white, dirty white to grayish, pink, or greenish when feeding on foliage (Rondon et al. 2007) (Figure 3). Larvae will reach the fourth and final instar 16 to 24 days after hatching during mid-summer conditions (Foot 1998).

Pupation occurs among stored potato tubers, dead potato leaves, or on the soil (Godfrey and Haviland 2008). Pupae are formed in a cocoon and usually covered with soil particles and debris. Pupae are approximately 1.9 cm (0.75 inches) in length with a smooth appearance (Rondon et al. 2007). During the mid-summer months, adult moths will emerge after six to nine days (Foot 1998).

Figure 3. Potato tuberworm larva and pupa (Larva drawing copied from Central Science Laboratory, Harpenden Archive, British Crown, Bugwood.org. http//www.invasive.org/browse/detail.cf...m=0176082; pupa photo copied from **International Potato Center, copied from** http://thepgi.com/resources/tuberworm-2007.pdf).

Previous studies have correlated the severity of tuberworm damage during a growing season to the numbers that are able to successfully overwinter (Lal 1987). Studies have also shown that potato tuberworm can survive subfreezing temperatures (Underhill 1926). Based on trapping information from 2004, potato tuberworm successfully overwintered in the southern Columbia Basin (Rondon et al. 2006). No specific life stage has definitively been determined to overwinter; eggs, larvae, and pupae can survive in environments such as cull piles, and unharvested tubers remaining under the soil surface (Rondon et al. 2007). Tuberworm do not enter diapause, or a hibernating state, and instead wait out the winter (Langford 1934). Those tuberworm that avoid disease, predation, freezing, dehydration, and starvation are able to infest potato tubers or foliage early in the spring. As many as eight generations per year may occur in sub-tropical areas. Each generation may span four to five weeks (Foot 1975). During the cooler seasons, the life cycle can be expected to last 20 to 24 weeks (Foot 1998). The optimum average daily temperatures for potato tuberworm development are between 20º C and 25º C (Raman 1998a). In the state of Washington, two or more generations will occur during the summer with possibly more occurring in storage during the winter months (Chittenden 1913, Rondon et al. 2006).

Tuberworm Damage

Damage from larval feeding on potato foliage is usually insignificant, although stem and leaf mining in young potato stands may stunt or reduce stand vigor when high larval numbers are present (Godfrey and Haviland 2008; Figure 4). The mining larvae damage leaves and tubers causing storage (Raman 1988b) and field problems (Fenemore

1988). Damage to leaves is usually unnoticeable, but in some instances can lead to reduced stand vigor (Rondon et al. 2007). The larvae cause severe damage typically resulting from tuber infestations (Figure 5). Early instar larvae often enter the tubers at or just underneath the soil surface (Godfrey and Haviland 2008). These larvae enter tubers at the eyes, leaving behind easily observed frass and webbing deposits. Thus, potato tuberworm damage can be distinguished from wireworms or other soil-inhabiting insects that have "clean" or frassless entry locations (Godfrey and Haviland 2008). Tubers located near soil cracks or soil surfaces are more susceptible to tuberworm infestation (Rondon 2007). Tubers remaining in the ground for prolonged periods after vine desiccation often experience more damage than tubers removed closer to vine desiccation (Godfrey and Haviland 2008). Vine desiccation is the period (approximately 2 weeks) after potato plant kill that is used to initiate skin set for harvest purposes. When vine desiccation begins, larvae will exit foliage and migrate to the soil. In storage conditions larvae can to crawl considerable distances to find tubers or other sites for pupation, such as crevices in walls, floors, and crates (Ferro and Boiteau 1993). Tuber infestations in storage can lead to potato rot and higher incidence of disease, which renders the potatoes unmarketable.

Figure 4. Potato tuberworm leaf damage (copied from UC Statewide IPM Program, 2007 University of California, http://www.ipm.ucdavis.edu/PMG/P/I-LP-POPE-CD.007.html).

Figure 5. Potato tuberworm tuber damage (copied from UC Statewide IPM Program, 2007 University of California, http://www.ipm.ucdavis.edu/PMG/P/I-LP-POPE-CD.007.html).

Pesticide Information

Introduction

The insecticides tested in this study have a broad range of characteristics. Each insecticide possesses a unique mode of action. Furthermore, these compounds represent a wide range of physicochemical properties and toxicity (Table 1). These parameters indicate how the compounds will distribute and react in the environment and potentially affect nontarget organisms.

Table 1. Toxicity and physicochemical properties of tested insecticides.

Active Ingredient	Mode of Action	Acute Oral LD_{50} Male Rat (mg/kg)	NOAEL (mg/kg)	Water Sol. (mg/L)	Vapor Pressure (Pa)
Methamidophos	Acetylcholinesterase Inhibition	17	< 2.0	90,000	3.0×10^{-9} @ 30º C
Indoxacarb	Sodium Ion Channel	1867	40	0.2	2.5×10^{-8} @ 25º C
Spinetoram	Nicotinic and GABA-gated ion channels	> 5000	> 2000	11.3	5.3×10^{-5} @ 20º C
Esfenvalerate	Sodium Ion Channel	458	125	0.002	1.5×10^{-9} @ 25º C

Methamidophos ((RS)-(O,S-dimethyl phosphoramidothioate))

Tuberworm can be controlled by various synthetic insecticides, including methamidophos (Dillard et al. 1993). Methamidophos (formulated as Monitor) is categorized as an organophosphorus (OP) insecticide. Most OPs control a broad spectrum of insect species. This compound has been shown to be consistently more toxic to beneficial insects, including bees, than other chemistries with different modes of action

(Symington 2003). Furthermore, methamidophos is the most acutely toxic compound to mammals that was used in this study (California EPA 2004) (Table 1).

The mode of action for methamidophos is the inhibition of acetylcholinesterase, which is an enzyme located in the central and peripheral nervous system and is responsible for breaking down the neurotransmitter acetylcholine (Sultatos 1994). Thus, acetylcholine builds in the synaptic clefts and causes hyperstimulation of the nervous system (Hayes et al. 1980). This stimulation causes convulsions and death (Abou-Donia 1992).

Methamidophos can move translaminarly in the potato plant, but it is not fully systemic (Antonious 1994). Thus, methamidophos bioactivity likely depends on direct contact activity with localized systemic action. Furthermore, this compound does not have an anti-feeding effect on newly arriving insects (Thackray et al. 2000).

Methamidophos exhibited a half-life of 0.7 – 0.9 days on tomato foliage (Evaristo and Casadei de Baptista 2002). This low level of persistence may counteract the high level of toxicity that exists among non-target organisms, by limiting the amount of time the product is present in the field after application. Methamidophos was a good candidate to test against potato tuberworm because many lepidopteran species show susceptibility, and it is frequently used in the Columbia Basin with applications targeting nearly 50% of the potato acreage (United States Department of Agriculture, 2006).

Esfenvalerate (*S*)-α-cyano-3-phenoxybenzyl (*S*)-2-(4-chlorophenyl)-3-methylbutyrate

Esvenvalerate (formulated as Asana) is a pyrethroid insecticide (Dupont 2002a). Pyrethroids are synthetic analogs of pyrethrins, one of several components in pyrethrum

extracts from the flowers of *Chrysanthemum cinerariifolium* (Asterales: Asteraceae). Pyrethrins and the synthetic pyrethroids are sodium channel modulators (Narahashi 2000). Esfenvalerate has a broad spectrum of activity and in some studies has shown decreased parasitism rates of hymenopterous insects after application (Viana et al. 2009) and is highly toxic to bees. However, pyrethroids are known to have some repellency against bees, which could lower the hazard of these compounds when bees are present (Moffett et al. 1982).

Pyrethroids are separated into two classifications, Type I or Type II, based on both chemical structure and biological effects of high-dose acute exposures (Gammon et al., 1981). Compounds that do not possess an α-cyano group on the phenoxybenzyl moiety produce aggressive tremors and sparring toxicity symptoms (Type I, or T-syndrome). Compounds that possess an α-cyano group on the phenoxybenzyl moiety produce less aggressive involuntary movement and salivation toxicity symptoms (Type II, or CS-syndrome). Compounds with mixed signs, including both tremors and salivation are labeled Type I/II or TS (Lawrence and Casida 1982; Verschoyle and Aldridge 1980). Both types inhibit the nervous system at the sodium ion channel, however, some type II pyrethroids will also affect the gamma-aminobutyric acid (GABA) neurotransmitter (Costa 1997).

Esfenvalerate is a type II pyrethroid (Ray 1991). In the insect nervous system, esfenvalerate binds to the sodium channels along the nerve cell axons and locks the channel open (Narahashi 2000, Soderlund et al. 2002). This results in repetitive firing of the nerves leading to insect disorientation and failed body functions. Esfenvalerate

rapidly paralyzes insects and causes feeding cessation after seven minutes of exposure (Hannig et al. 2009). Asana is not a highly acutely toxic compound to mammals (California EPA 2001) (Table 1).

Esfenvalerate has a relatively short half-life of 1.0 to 1.6 days on broccoli leaves (Antonious 2002). As with methamidophos, short persistence of esfenvalerate will limit adverse effects on non-target organisms. Esfenvalerate was a good candidate to test against potato tuberworm because its mode of action is different from OP insecticides and could thus be used in insect resistance management that rotates pesticides. Also, Asana is already being used on approximately 60% of potato acreage for insect control of Colorado potato beetle and beet leafhopper (United States Department of Agriculture, 2006).

Indoxacarb methyl (*S*)-*N*-[7-chloro-2,3,4a,5-tetrahydro-4a-(methoxycarbonyl)indeno[1,2-*e*][1,3,4]oxadiazin-2-ylcarbonyl]-4-(trifluoromethoxy)carbanilate

Indoxacarb (formulated as Avaunt) is an oxadiazine, which makes treated insects stop feeding and go into mild convulsions or permanent paralysis (Tillman et al. 2001). This compound blocks the sodium channel and is reported to be a slow-acting insecticide with relatively long residual activity (Andaloro 2000). Indoxacarb is especially active on foliar-feeding lepidopteran larvae (Sansone and Minzenmayer 2000) but has low toxicity to beneficial organisms, including bees (Bostanian and Akalach 2006).

Indoxacarb is rapidly bioactivated to a N-decarbomethoxylated metabolite (DCMP) that is a potent blocker of the voltage-dependent sodium channel (Wing et al. 2000). While pyrethroids hold the sodium channel open in nerve cells, indoxacarb blocks the channel, essentially causing the channel to close. Sucking insects may be able to

withstand higher concentrations of indoxacarb, and while capable of absorbing and bioactivating indoxacarb after oral administration, they do so more slowly than Lepidoptera (Wing et al. 2000). Susceptible pests exposed to Avaunt stop feeding within four hours after application. The higher the application rate, the quicker feeding stops. At four to 48 hours after exposure larval paralysis and death occur (Dupont 2002b). Indoxacarb is far less acutely toxic to mammals than methamidophos and esfenvalerate as shown in Table 1 (California EPA 2008).

Indoxacarb is highly lipophilic and absorbs into a leaf's waxy cuticle (Dupont 2000b). This insecticide also possesses moderate translaminar movement once on the leaf surface. The half-life of this compound has been reported as 3.0 to 3.8 days on eggplant foliage, which is longer than the other compounds evaluated in this study (Saimandir 2009). Although indoxacarb has the longest half-life of the products tested in this study, its selectivity for Lepidoptera suggests a low hazard to non-target organisms when used under field conditions. Indoxacarb is a good candidate for testing against tuberworm populations because this compound's use on potatoes is increasing and its unique mode of action could be exploited as a resistance management tool involving chemical class rotations.

Spinetoram (3'ethoxy, 5,6-dihydro spinosyn J):
(2R,3aR,5aR,5bS,9S,13S,14R,16aS,16bR)-13-{[(2S,5S,6R)-5-(dimethylamino)-6 methyltetrahydro-2Hpyran- 2-yl]oxy}-9-ethyl-14-methyl-7,15-dioxo 2,3,3a,4,5,5a,5b,6,7,9,10,11,12,13,14,15,16a,16b-octadecahydro-1H-as-indaceno[3,2 d]oxacyclododecin-2-yl 6-deoxy-3-O-ethyl-2,4-di-O-methyl-beta-L-mannopyranoside

Spinetoram (formulated as Delegate) is one of a small class of insecticides called spinosyns that are derived from fermentation products of *Saccharopolyspora spinosa*

(Mertz and Yao 1990). This insecticide controls many insect species, especially lepidopterans such as tobacco budworm (*Heliothis virescens*) and southern armyworm (*Spodoptera eridiania*), but it has a low impact on beneficial insects (Kirst et al. 1992). Spinetoram is moderately toxic to bees and aquatic organisms (Averill and Sylvia 2009).

The spinetoram compound causes excitation of the insect nervous system by altering the function of nicotinic and GABA-gated ion channels (Millar and Denholm 2007). Overall, it is more active than spinosad and has an expanded spectrum of bioactivity while maintaining the exceptional environment and toxicological profile, as shown in Table 1, that is associated with the spinosyn insecticide products (Huang et al. 2009). Spinetoram is the least toxic compound to mammals as shown in Table 1 (California EPA 2007).

Spinetoram is rapidly biodegraded in the environment and is susceptible to photolysis in water. Studies have shown very short half-lives of approximately eight hours after application on lettuce leaves (Australian Pesticides and Veterinary Medicines Authority 2008). With a low toxicity and half-life, this compound poses a very reduced risk to non-target organisms. Spinetoram was a good candidate to test against potato tuberworm because it is a new compound with excellent efficacy against lepidopteran species combined with a low toxicity to natural enemies. Also, this product can be incorporated in integrated pest management strategies to reduce the potential incidence of insect resistance (Dow AgroSciences 2006).

Purpose of Study

Recent PTW infestations in fields located in the Columbia Basin warrant an examination of the efficacy of insecticide active ingredients currently registered for use on potatoes. The data generated by this project will have two important uses. First, determination of current tuberworm susceptibility level to insecticides used for control can be used to track changes in susceptibly over time. Second, if poor insecticide performance claims are made and resistance is the suspected reason for the lack of efficacy, populations could be collected and bioassayed for comparisons of mortality to historical standards of a susceptible laboratory population.

Materials and Methods

Acquisition and Handling of Larvae

Eggs were obtained from Dr. Lerry Lacey's lab at the United States Department of Agriculture Agricultural Research Station's (USDA-ARS) research facility in Wapato, Washington. The PTW colony at the USDA-ARS Wapato station was acquired from live specimens captured in the Columbia Basin in 2005. Eggs were shipped overnight prior to testing and kept below a temperature of 10º C (50º F) until testing was initiated. Approximately two days prior to testing, the eggs were transferred from the original incubator to a warmer incubator set at 27.0º C (80.6º F) to cause hatching at the desired time, which also ensured all larvae were at the appropriate age (less than 24 hours) for testing.

Preparation of Stock and Test Solutions

First, an initial stock solution of pesticide (Cpd_1) was prepared for each of the four compounds by weighing 1.0 gram of formulated product and adding de-ionized water to reach a 100 mL volume. The initial solution concentration was chosen to be above the highest labeled application rate. From Cpd_1, 1.0 mL was diluted hundred-fold with de-ionized water to create a second stock solution (Cpd_2). A nonionic surfactant (NIS) was added to Cpd_2 at a rate of 0.25%. Cpd_2 was the stock solution from which a 2-fold dilution series of solutions were prepared using deionized water as the diluent. The dilution series of solutions was prepared with sufficient NIS so that the final surfactant concentration was 0.25%. The serial dilutions of Cpd_2 were prepared as needed on the day of testing. The Cpd_1 and Cpd_2 stocks were held under refrigerated conditions of 4.0º C (39.0º F) to prevent degradation of the active ingredient by microbial bioactivity or UV light.

Determination of LC_{50} and LC_{95}

Final testing for each product was initiated only after preliminary studies were conducted to determine best practices for conducting bioassays with neonate tuberworms on treated potato leaf disks. The basic bioassay procedure consisted of exposing neonate tuberworms to individually treated potato leaf disks. Untreated Ranger Russet potato leaves were used for this study because this variety is common to the Columbia Basin and were readily available.

Each pesticide dilution set was prepared prior to testing, and one pesticide was tested during a given testing period. Each test contained a control which consisted of de-

ionized water with 0.25% non-ionic surfactant. Four replications of each pesticide concentration were used in the experimental design.

Potato leaves were harvested within two weeks of bioassay testing and held at 4.0º C (39º F). One-inch diameter potato leaf disks were punched just prior to pesticide treatment and placed in Solo plastic 1¼ oz (37.0 ml) containers. Each leaf disc was treated with insecticide by pipetting 100 µL (0.1 mL) of a given solution on the upper surface of each disk. Since all treatments contained a non-ionic surfactant, all treatments showed similar coverage across the leaf surface. Careful attention was made to ensure that all applications were manually spread across the entire leaf disc using the pipette to uniformly spread the solutions. This step was performed to ensure even coverage of the leaf discs and to minimize pooling of solution on the leaf discs. The leaf disks were then allowed to dry for one hour, at which time five neonate larvae (<24 hours post hatching) were individually placed on each disk with a small paintbrush. Immediately after placing the five larvae on the leaf disc, a lid was placed on the container to minimize volatilization losses of insecticides. To reduce cross-contamination concerns, only one insecticide was tested at a time.

After placing all larvae, bioassay containers were held in an incubator at 27.0º C (80.6º F). Each sample was evaluated at three and 24 hours after larval placement on leaves. Containers holding the treated leaf disks were examined under a dissecting microscope to count total numbers of live and dead larvae. Larvae were considered dead if they did not move when prodded or if larvae took longer than five seconds to roll over

when oriented with their dorsal surface facing the substrate. After 24 hours the samples were discarded.

Determination of LT_{50} and LT_{95}

Procedures similar to the LC50 bioassays were used to characterize the length of time between initial exposure and mortality for the larval assays. However, only one solution concentration, namely the concentration corresponding to the estimated LC95, was tested. The same quantity of solution was applied to each leaf disc (0.1 mL) and a one-hour drying time was allowed before five neonate larvae were placed on the upper leaf surface. One notable difference from the LC50 bioassays was the use of eight replications instead of four. Eight replications were used in this study to reduce variability and increase precision within the results. The number of dead larvae in each replicate container was counted at time intervals of 5, 15, 30, 60, and 120 minutes after placing them on the leaf discs.

Data Analysis

Probit analysis using the PROC PROBIT routine of SAS (Statistical Analysis System software, PC ver. 9.1) was used to estimate the LC50/LC95 and LT50/LT95 with related statistical parameters (95% fiducial limits [FL], slope, standard error [SE], and chi-square). Abbott's formula (Abbott 1925) was used to correct the response at each pesticide concentration for control mortality.

Probit analysis of dose-response data has many advantages (Bliss 1934). First, this analysis shows that the variation in susceptibility among individuals is normal and the effectiveness of the concentration increases in proportion to the logarithm. Second,

this method determines whether the exposed tuberworms were in a homogeneous population and if the experimental amounts were uniformly proportional to the effective concentrations over the entire range covered by the experiment. Third, probits increase the understanding of how compound toxicity changes throughout the dosage range, as indicated by change in slope. Fourth, using probits provides the ability to express the uniformity and diversity among susceptible individuals when in contact with a toxic agent (Bliss 1934). In addition to estimating the LC and LT endpoints, the minimum and maximum fiducial limits were calculated to determine the extent of heterogeneity within the population.

Graphs for the LC and LT data sets were constructed to show the calculated percentage mortality in relationship to the empirical observations. The fiducial limits were also included in the graphs to show heterogeneity of the population. The tighter fiducial limit curves are to the calculated values, the less heterogeneity exists among the population response to concentration and time (LC and LT, respectively).

All concentrations obtained (actual and calculated) were converted into an active ingredient (lb) per acre value to determine the relationship between the results and actual product label rates. These per acre values were graphed and displayed in Appendix A. The conversion for each insecticide from recommended product label rates to the appropriate solution concentration is shown in Table 2. First, the label rates were converted to the amount of product per square centimeter ($\mu g/cm^2$) to correspond to the concentrations used in the statistical analysis. This mass per unit area was then converted to product concentration per milliliter ($\mu g/mL$) of solution placed on the leaf discs. Using

these conversions, label rates, which are based on amounts (lbs) of product per area (acre), can be compared to solution rates, which are based on amounts of product per solution volume.

Table 2. Conversion table for active ingredients.

Active Ingredient	Labeled App. Rate (lb a.i./acre)	Mass/unit area (µg product/cm^2)	Corresponding Sol. Concentration (µg product/mL)
Methamidophos	0.75-1.0	21.2-28.2	1071-1429
Indoxacarb	0.056-0.11	2.1-4.1	106.6-209.4
Spinetoram	0.047-0.0625	2.1-2.8	107.4-142.8
Esfenvalerate	0.015-.05	2.0-6.7	101.9-350.0

The persistence data over 14 days for each compound were modeled using literature half-life values and then graphed as a function of mortality based on the 24 hour LC results (Appendix C). Half-lives were from studies of residue persistence on various representative crops because potato foliage data were not available. The first step in this analysis used the half-lives in a first order model to predict an expected chemical concentration on a daily basis for 14 days after application using the highest labeled rate. These daily modeled concentrations were then compared to the corresponding estimated concentration-mortality data coordinates obtained in the probit analysis of the 24 hour bioassays. From this comparison, a plot was made of the expected mortality for any modeled concentration on any given day. In summary, the concentration expected to remain on the leaf surface each day after application was calculated and assigned a mortality value based on the probit-generated mortality rate for concentrations in the 24 hour bioassay data set.

Results

Nearly all tested PTW died when exposed to surface concentrations of the four insecticides that were at least an order of magnitude less than the recommended field application rate. The dose-response data (LC_{50} and LC_{95}) are shown for each active ingredient in Table 3. The time response data (LT_{50} and LT_{95}) for each insecticide are shown in Table 4. The chi-square associated with the slope estimates for the dose-response functions was used to assess whether the actual mortality observations were different from the predicted values of response given the probit model. The null hypothesis is that no relationship exists between concentration and mortality. The results are significant if the chi-square value is $p < 0.05$ and, therefore, the null hypothesis can be rejected. Chi-square tests for all insecticide bioassays were significant, suggesting that there was significant trend for increase in PTW mortality with exposure to higher insecticide concentrations. The expected persistence results are provided in Appendix C for each compound in this study.

Table 3. Comparison of toxicities of active ingredients (LC_{50} and LC_{95}) at 3 and 24 hour after exposure of neonate larvae to treated potato leaf disks.

Active Ingredient	Time	n	LC_{50} (95% FL) x 10^{-3} lb AI/acre	LC_{95} (95% FL) x 10^{-3}, lb AI/acre	Slope	X^2 (df)
Methamidophos	3	87	29.2 (22.4 – 54.4)	46.7 (36.1 – 129)	0.30	6.83 (1)
Methamidophos	24	87	23.1 (17.0 – 31.2)	38.0 (30.3 – 62.7)	0.39	11.5 (1)
Indoxacarb	3	115	1.43 (0.453 – 2.92)	38.7 (13.8 – 527)	1.15	16.4 (1)
Indoxacarb	24	126	0.026 (0.000 – 0.230)	26.9 (4.99 – 29100000)	0.55	4.68 (1)
Spinetoram	3	225	2.84 (1.74 – 4.37)	10.7 (7.98 – 16.6)	0.47	25.5 (1)
Spinetoram	24	226	0.148 (-0.222 – 0.408)	1.84 (1.27 – 3.56)	2.16	14.2 (1)
Esfenvalerate	3	141	0.0126 (0.004 – 0.025)	0.409 (0.176 – 2.24)	1.09	23.8 (1)
Esfenvalerate	24	145	0.006 (0.001 – 0.013)	0.224 (0.0975 – 1.28)	1.05	20.1 (1)

Table 4. Comparison of time to lethal response (LT50 and LT95) by neonate PTW larvae exposed to leaf disks treated with LC95 equivalents of insecticides.

Active Ingredient	n	LT_{50} (95% FL), time (min)	LT_{95} (95% FL), time (min)	Slope	X^2 (df)
Methamidophos	192	75 (65-87)	146 (126-179)	0.023	64 (1)
Indoxacarb	188	53 (41-68)	159 (129-217)	0.016	37 (1)
Spinetoram	199	26 (21-30)	58 (50-72)	0.051	51 (1)
Esfenvalerate	200	11 (8-13)	25 (21-33)	0.119	30 (1)

Methamidophos

The assays indicate that the methamidophos LC_{50} was 824 x 10^{-3} µg/cm^2 (29.2 x 10^{-3} lb a.i./acre) and 65.2 x 10^{-3} µg/cm^2 (23.1 x 10^{-3} lb a.i./acre) after three and 24 hours of exposure, respectively (Table 3). The LC_{95} value was established at 1371 x 10^{-3} µg/cm^2 (46.7 x 10^{-3} lb a.i./acre) and 1072 x 10^{-3} µg/cm^2 (38.0 x 10^{-3} lb a.i./acre) after three and 24 hours, respectively (Table 3).

The labeled field methamidophos application rates are 0.75 – 1.0 lb a.i./acre. These rates would be expected to provide 100% control of PTW larvae. At three hours after application, the estimated LC_{50} for methamidophos was equivalent to approximately 4.0% of the lowest labeled rate of application (Figure 6). The estimated LC_{95} value at three hours after application corresponded to a product rate that was nearly 6.5% of the lowest label rate (Figure 7). At 24 hours after application, percentage mortality of PTW larvae was similar to that observed after three hours. The fiducial limits are wide near the 3-h LC_{50}, but much narrower in the 24-h test showing greater certainty in determining the true confidence interval for each compound.

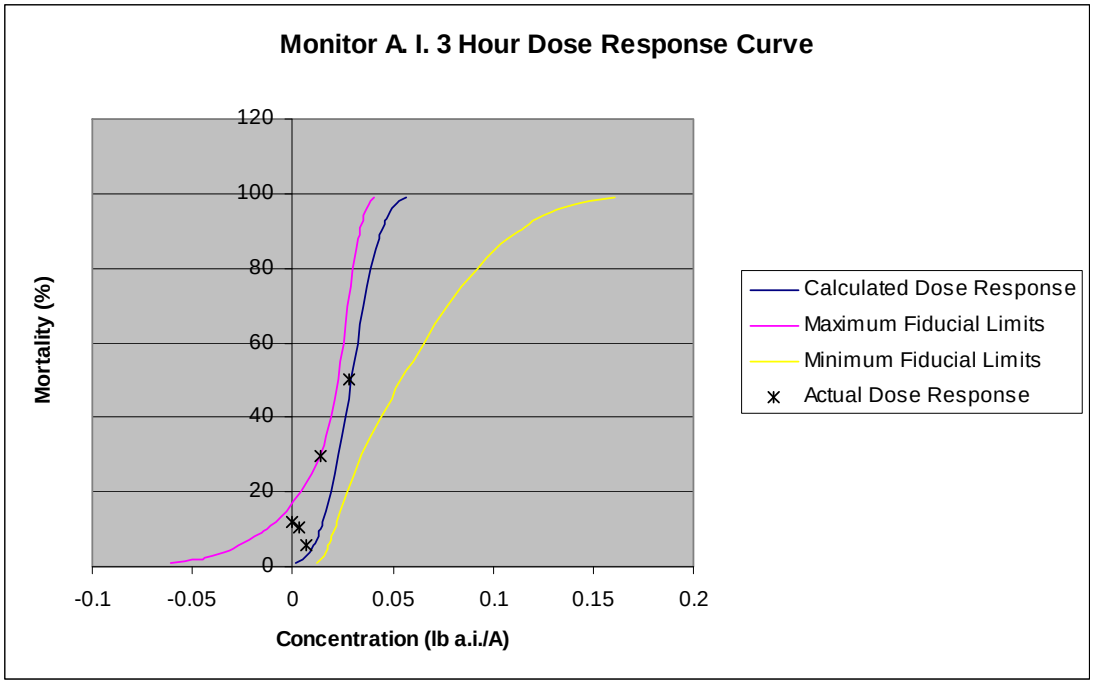

Figure 6. Monitor 3 hour active ingredient dose response curve.

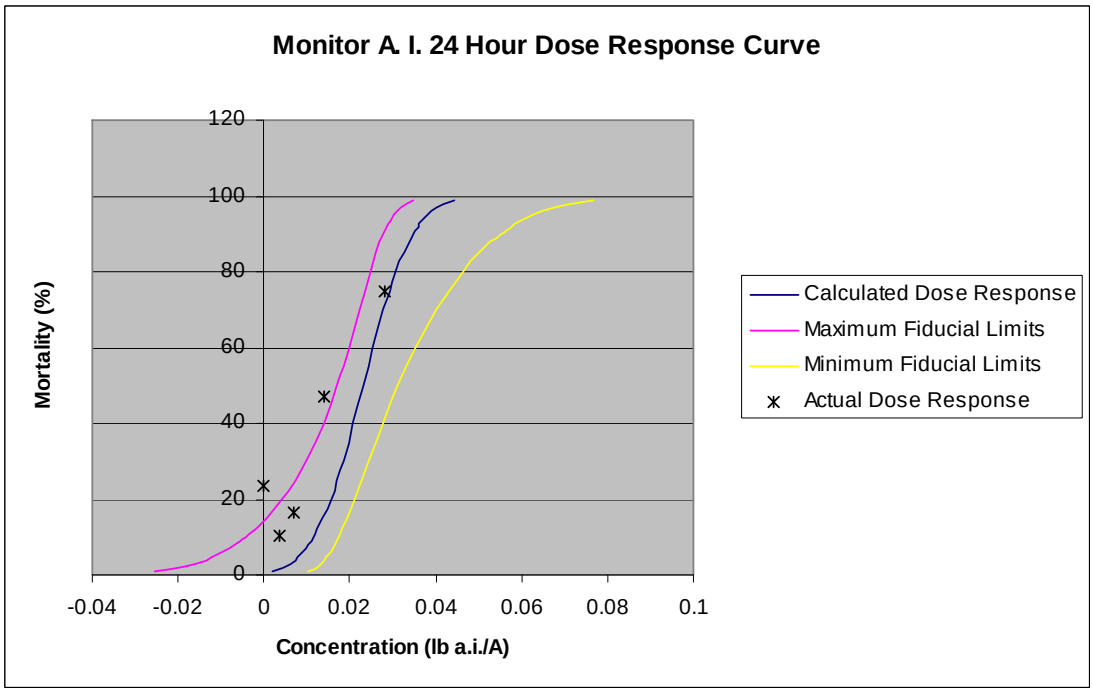

Figure 7. Monitor 24 hour active ingredient dose response curve.

When larvae were exposed to methamidophos at the estimated LC_{95} concentration, mortality increased proportionally to time of exposure. Mortality was not observed until the 15 minute exposure interval (10% mortality), but then it doubled for each subsequent evaluation period. For the last observation interval of 120 minutes, methamidophos had killed 85% of the exposed larvae. Methamidophos caused 50% larval mortality in approximately 75 minutes, but approximately 146 minutes was required to kill 95% of the test population (Table 4) (Figure 8).

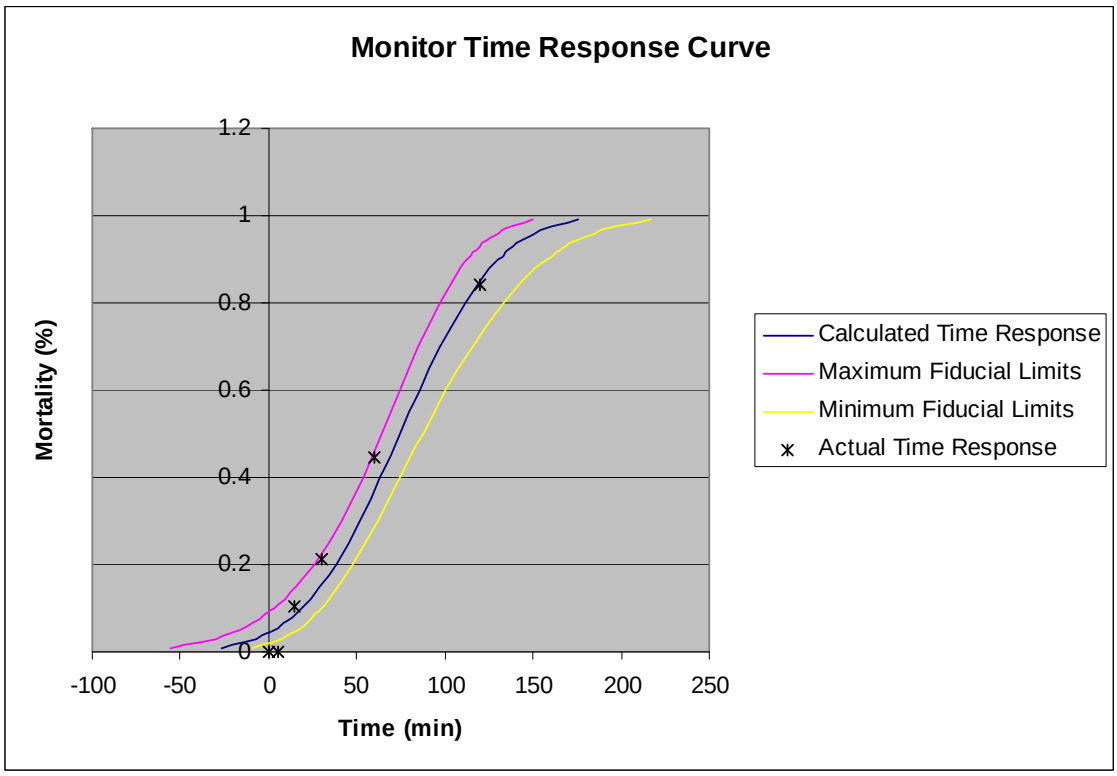

Figure 8. Monitor LT data.

The modeled persistence data for methamidophos (Appendix C, Figure C-1) showed that at the high label rate, 100% larval mortality (100%) can be expected on foliage until approximately 4 days after application when it is predicted to decrease rapidly. At eight days after application less than 5% of the larval population would have been killed.

Indoxacarb

Indoxacarb had an LC_{50} of 54 x 10^{-3} µg/cm^2 (1.43 x 10^{-3} lb a.i./acre) and 9.74 x 10^{-3} µg/cm^2 (0.0259 x 10^{-3} lb a.i./acre), after three and 24 hours, respectively, of PTW exposure to treated leaf disks (Table 3). The LC_{95} value was determined to be 1460 x 10^{-3} µg/cm^2 (38.7 x 10^{-3} lb a.i./acre) and 1010 x 10^{-3} µg/cm^2 (26.9 x 10^{-3} lb a.i./acre) after three and 24 hours of exposure, respectively (Table 3).

The labeled field rates for indoxacarb are 0.056 – 0.11 lb a.i./acre. Based on the results from this study, the labeled use rates for indoxacarb would be expected to provide over 95% control at three and 24 hours after application. At three hours after application, the concentration that provided the LC_{50} for indoxacarb corresponded to a product rate approximately 2.5% of the lowest labeled rate concentration (Appendix A, Figure A-1). At the LC_{95} equivalent concentration three hours after application, the modeled indoxacarb concentration corresponded to a product rate that was approximately 50% of the low label rate. At 24 hours after application, indoxacarb provided increased control of potato tuberworm larvae. The three and 24 hour mortality trends were similar with the LC_{50} for indoxacarb corresponding to an application rate that was 3 orders of magnitude

lower than the low labeled rate, while the LC_{95} value corresponded to a product rate that was approximately 50% of the low labeled rate (Appendix A, Figure A-2). The wide fiducial limits show a lot of uncertainty about the estimates of mortality at the given concentration.

Indoxacarb quickly killed larvae initially (10% mortality within 5 min), but mortality leveled off as the study progressed (Appendix B, Figure B-2). This mortality more than doubled at the next time interval (15 minutes). At each subsequent interval, however, mortality increased at a slower rate with only a 20% increase in mortality from the 60 minute to 120 minute interval. At 120 minutes, the final evaluation timing, indoxacarb resulted in over 80% mortality. Probit analysis estimated LT_{50} and LT_{95} values of approximately 53 minutes and 159 minutes, respectively (Table 4). The comparatively narrow fiducial limits associated with the time-response curve suggested a high level of homogeneity in the tested PTW population (Appendix B, Figure B-2).

The modeled persistence data for indoxacarb (Appendix C, Figure C-2) showed that at the high label rate, this product can be expected to cause high larval mortality (98%) that would last for nearly 14 days when mortality would drop to about 88%.

Spinetoram

Spinetoram had LC_{50} estimates of 128 x 10^{-3} µg/cm^2 (2.84 x 10^{-3} lb a.i./acre) and 6.65 x 10^{-3} µg/cm^2 (0.147 x 10^{-3} lb a.i./acre) after three and 24 hours of exposure, respectively. (Table 3). The LC_{95} value was determined to be 482 x 10^{-3} µg/cm^2 (10.7 x 10^{-3} lb a.i./acre) and 83.0 x 10^{-3} µg/cm^2 (1.84 x 10^{-3} lb a.i./acre) after three and 24 hours, respectively (Table 3).

The labeled application rates for spinetoram on potatoes are 0.0468 – 0.0625 lb a.i./acre. These rates should provide 100% control of PTW larvae. At three hours after application, the estimated LC_{50} for spinetoram was the equivalent to a product rate that was approximately two orders of magnitude lower than the lowest label rate. The estimated LC_{95} value at three hours after application corresponded to a product rate that was 22% of the lowest labeled rate concentration (Appendix A, Figure A-3). At 24 hours after application, mortality of potato tuberworm larvae increased. The three and 24 hour mortality trends were similar with the LC_{50} for spinetoram corresponding to an application rate that was more than 2 orders of magnitude lower than the low labeled rate, while the LC_{95} value corresponded to a product rate that was more than one order of magnitude lower than the low labeled rate (Appendix A, Figure A-4). The fiducial limits are narrow near the 3-h and 24-h LC_{50}. The fiducial limits about the LC_{50}s show a large mortality separation among concentrations and higher concentrations causing higher mortality.

When larvae were exposed to spinetoram at the estimated LC_{95} concentration, mortality increased directly to time of exposure. Mortality was noticed quickly at the 5 minute mark with 10% mortality. This mortality more than doubled at the next time interval (15 minutes). Between the 15 minute and 30 minute intervals the mortality rate had the greatest increase from 28% to 72% mortality. The mortality rate then started to plateau between the 30 minute and the 60 minute interval. At 120 minutes, the final evaluation timing, spinetoram caused 100% mortality. Spinetoram caused 50% larval mortality in approximately 26 minutes and approximately 58 minutes was required to kill

95% of the test population (Tables 4). Fiducial limits associated with the dose-response curves were very narrow compared to the fiducial limits of the dose-respones curves, suggesting a high degree of homogeneity in response (Appendix B, Figure B-3).

The modeled persistence data for spinetoram (Appendix C, Figure C-3) showed that at the high label rate, 100% larval mortality (100%) can be expected on foliage until one day after application when it is predicted to decrease rapidly. At three days after application less than 50% of the larval population would likely be killed.

Esfenvalerate

Esfenvalerate had an LC_{50} of 1.69 x 10^{-3} µg/cm^2 (0.0126 x 10^{-3} lb a.i./acre) and 0.808 x 10^{-3} µg/cm^2 (0.006 x 10^{-3} lb a.i./acre) after three and 24 hours of exposure, respectively (Table 3). The LC_{95} value was determined to be 54.9 x 10^{-3} µg/cm^2 (0.409 x 10^{-3} lb a.i./acre) and 30.2 x 10^{-3} µg/cm^2 (0.224 x 10^{-3} lb a.i./acre) after three and 24 hours, respectively (Table 4).

The labeled field application rates for esfenvalerate are 0.015 – 0.05 lb a.i./acre. After three hours after application, the estimated LC_{50} for esfenvalerate was the equivalent of approximately three orders of magnitude lower than the lowest labeled rate of application. The estimated LC_{95} value at three hours after application corresponded to a product rate that was approximately 1% of the high label rate (Appendix A, Figure A-5). The three and 24 hour mortality trends were similar with the LC_{50} for esfenvalerate corresponding to an application rate that was nearly four orders of magnitude lower than the high labeled rate, while the LC_{95} value corresponded to a product rate that was approximately two orders of magnitude lower than the low labeled rate (Appendix A,

Figure A-6). The fiducial limits are wide near the 3-h LC_{50} because the data are not very robust. The wide limits are having tested comparatively fewer larvae than are normally tested. The fiducial limits about the LC50 are narrower in the 24 h test than in the 3 h test showing a more robust data set. This narrow width may be due to larger separation in tuberworm response among concentrations and higher concentrations producing higher mortality than lower concentrations.

When larvae were exposed to esfenvalerate at the estimated LC_{95} concentration, mortality increased proportionally to time of exposure. Esfenvalerate caused the quickest larval mortality of all compounds tested. Mortality was observed at just 5 minutes after placing larvae on the leaves. At 15 minutes, 65% of the larvae had died, and by 30 minutes 100% mortality was observed (Appendix B, Figure B-4). Esfenvalerate caused 50% larval mortality in approximately 11 minutes, but approximately 25 minutes was required to kill 95% of the test population (Tables 4). Fiducial limits associated with the time-response curves were very narrow compared to the fiducial limits of the dose-respone curves, suggesting a high degree of homogeneity in response (Appendix B, Figure B-4).

The modeled persistence data for esfenvalerate (Appendix C, Figure C-4) showed that at the high label rate, 100% larval mortality (100%) can be expected on foliage until five days after application when it is predicted to decrease rapidly. At 14 days after application less than 40% of the larval population would likely be killed if exposed to this level of concentration.

Discussion

LC Tests

The LC results show that all compounds used in this study were effective at controlling neonate potato tuberworm populations on potato leaves as compared to an untreated control. By testing many concentrations of each compound, the LC_{50}/LC_{95} were established and compared to product label field rates. Esfenvalerate proved to be the most acutely toxic compound in this study, followed by spinetoram, methamidophos, and indoxacarb based on LC_{50}/LC_{95}. At the three and 24 hour evaluations, esfenvalerate provided control of PTW larvae with smaller amounts of active ingredient, compared to the label rates, as compared to the other compounds in the study. It is possible that indoxacarb was less efficacious because this compound has a slower mode of action due to it having to be ingested and metabolized to DCMP, the bioactive metabolite. The other products in the study have modes of action that do not require metabolism first to an active metabolite. Furthermore, esfenvalerate is comparatively the most hydrophobic compound and likely diffuses across the waxy integument the fastest, thereby causing the quickest mortality response.

Slope

Slope of the dose-response function is an indication of the genetic diversity associated with response within a test population. A PTW population exhibiting a comparatively steep slope in response to one insecticide is likely dominated by either mostly susceptible individuals or resistant individuals. If the population response showed a flatter slope, more heterozygous individuals are likely to make up the population. Such

a population is more easily selected for resistance as continued selection pressure would quickly eliminate susceptible genotypes. To determine resistance development, two populations can be bioassayed and the slopes of the dose-response functions compared. Given that the PTW population tested in this study was from a lab colony and presumed to be highly susceptible to insecticides, those compounds exhibiting the steepest slopes in the dose-response function are comparatively the least likely to develop resistance. Both esfenvalerate and spinetoram had steep slopes compared to methamidophos and indoxacarb at the three hour evaluation. These results show that there is little diversity in the population response between susceptible and possibly resistant individuals to esfenvalerate and spinetoram. At the 24 hour evaluation the results were similar, although at this timing indoxacarb also showed a steep slope as well. In contrast, methamidophos yielded the flattest slope, suggesting a heterogeneous population response. Thus, esfenvalerate, spinetoram, and indoxacarb are less likely to cause resistance among the tuberworm population than methamidophos. However, the speed of resistance development will depend ultimately on the intensity of selection pressure, and whether resistance management tactics are used. One such tactic is rotating chemical use by mode of action, preferably using only one type of mode of action within a growing season.

LT Tests

The products that kill the fastest are likely to function most efficiently under environmental conditions given the tuberworm propensity to disperse and the heterogeneous residue distributions in the plant canopy. The LT results show that all

compounds used in this study would provide high levels of control within two hours of application. Esfenvalerate proved to cause the fastest mortality of any compound in this study as evidenced by its low LT_{50}, followed in order by spinetoram, indoxacarb, and methamidophos. Esfenvalerate started to cause PTW mortality after only 5 minutes of exposure as compared to 10 minutes for the other products. This trend was similar for the LT_{95} results, except methamidophos provided a slightly smaller LT value than indoxacarb. Again, indoxacarb may have been less efficacious because this compound has a slower mode of action due to it having to be ingested and metabolized to a bioactive metabolite. The time-response functions for all insecticides had steep slopes with the steepest exhibited by esfenvalerate and spinetoram.

Fiducial Limits

Fiducial limits are partly a function of the quality of the data set. The wider the fiducial limits the greater the heterogeneity of the population in response to a compound. The LC fiducial limits for this study were wider than the LT fiducial limits for all compounds. This was most likely due to the LT study having a more robust data set with eight replications, and therefore, more observations. Furthermore, the LT data followed a consistent trend with mortality increasing with increasing time. In contrast the LC data did not follow a consistent trend and at times the data showed a decrease in mortality at a comparatively higher concentration. Uncertainty in dose-response modeling may be due to insufficient numbers of larvae tested, high control mortality, little separation in tuberworm response among concentrations, and lower mortalities at higher concentrations than at lower concentrations. In this study, a larger data set with more

observations would most likely give results with narrower fiducial limits and greater certainty in determining the true confidence interval for each compound.

Persistence Modeling

The persistence modeling for each compound suggested that indoxacarb would be biologically active in the environment for the longest period of time followed by esfenvalerate, methamidophos, and spinetoram. Although modeling of esfenvalerate bioactivity suggested field control of PTW for five days after application, residues could volatilize very quickly because the compound has a very low water solubility that would contribute to a moderate Henry's Law constant. Spinetoram is moderately water soluble with a moderate vapor pressure, but has is rapidly degraded by photolysis. Therefore, this product can be expected to provide quick knockdown of pests but should not be considered as a compound with long residual activity.

Overall, esfenvalerate proved to be more efficacious across all aspects of this study than the other compounds tested. Spinetoram was also a very effective product in these studies, but with such a short half-life, it should not be expected to provide extended control. Indoxacarb may not provide the highest level of control in comparison to compounds like esfenvalerate and spinetoram, but control should be expected for longer periods of time after application. The bioassays also showed methamidophos to be consistently less efficacious than the other products in this study, which is similar to the assays reported by Symington and Horne (1998).

Future Studies

Many studies can be performed to better understand the efficacy of the compounds investigated in this study. All of the insecticides are sufficiently persistent to cause mortality for at least 24 hours or longer. Studies that focus on mortality after 24 hours are important in determining the actual length of time that bioactivity will persist in the field. Furthermore, since many compounds cause the pest to stop feeding and thereby prevent damage, studies that evaluate the feeding time and damage after application are important to determine the level of control that can be expected. Evaluating tubers, instead of leaves, can also be important to determine the influence of food source on bioactivity and should be considered in future studies.

Conclusion

Potato tuberworm continues to be a pest of concern for potato growers in the Pacific Northwest. This study was performed to determine the susceptibility of various insecticides that are available for tuberworm control. It is important to note that while insecticides are an inexpensive and effective control measure, other tools (biological and cultural) should be utilized to ensure the most effective pest control program, while guaranteeing that pest resistance to insecticides will not occur.

In this study, each evaluated product is very different in mode of action, use rates, and timing parameters. Some insecticides, such as esfenvalerate and spinetoram, offer quick knockdown ability, while others (e.g., indoxacarb) may provide longer efficacy. It

is important to understand how a specific insecticide works in order to provide the best control with the proper timing of application.

Based on this study, all products caused mortality of neonate tuberworm larvae at concentrations significantly below the product label application rates. PTW mortality occurred most slowly during exposure to methamidophos but the insecticide still provided adequate control below the labeled rate range. This product can be expected to provide control for approximately one week following the initial application. Indoxacarb also caused larval mortality at concentrations that were within the labeled rate range. This product acts more slowly than the other products in the study, but indoxacarb was predicted to have the longest residual bioactivity of any product tested. Spinetoram proved to be a very good product in this study because it killed quickly at the labeled rate ranges. Furthermore, this product was very efficacious at rates much lower than the label rate range. Judging by the persistence data, however, this compound will become less efficacious after just a couple of days after application. Esfenvalerate was also very toxic to tuberworm larvae in this study, causing mortality at levels well below the label rate range. Esfenvalerate can be expected to provide quick knockdown of pest populations, while giving adequate control for over a week after the first application.

In summary, all products in this study, applied at the right timing and rate, will provide control of potato tuberworm in the Pacific Northwest.

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APPENDICES

APPENDIX A.
LC_{50} Data Figures.

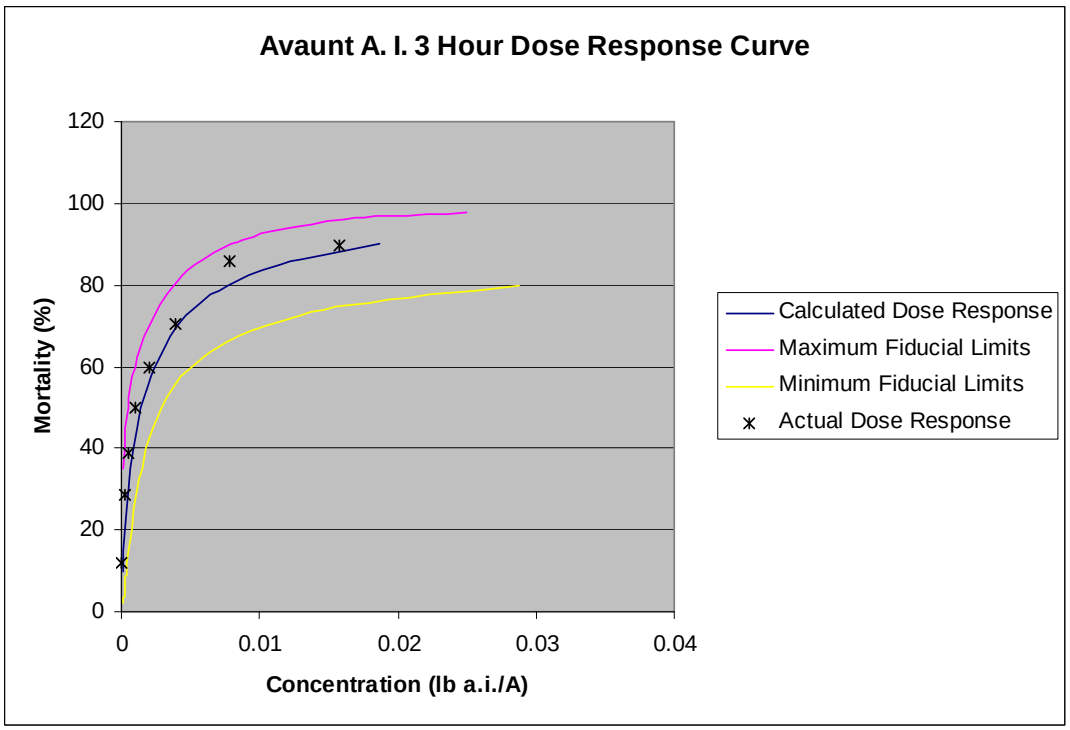

Figure A-1. Avaunt 3 hour active ingredient dose response curve.

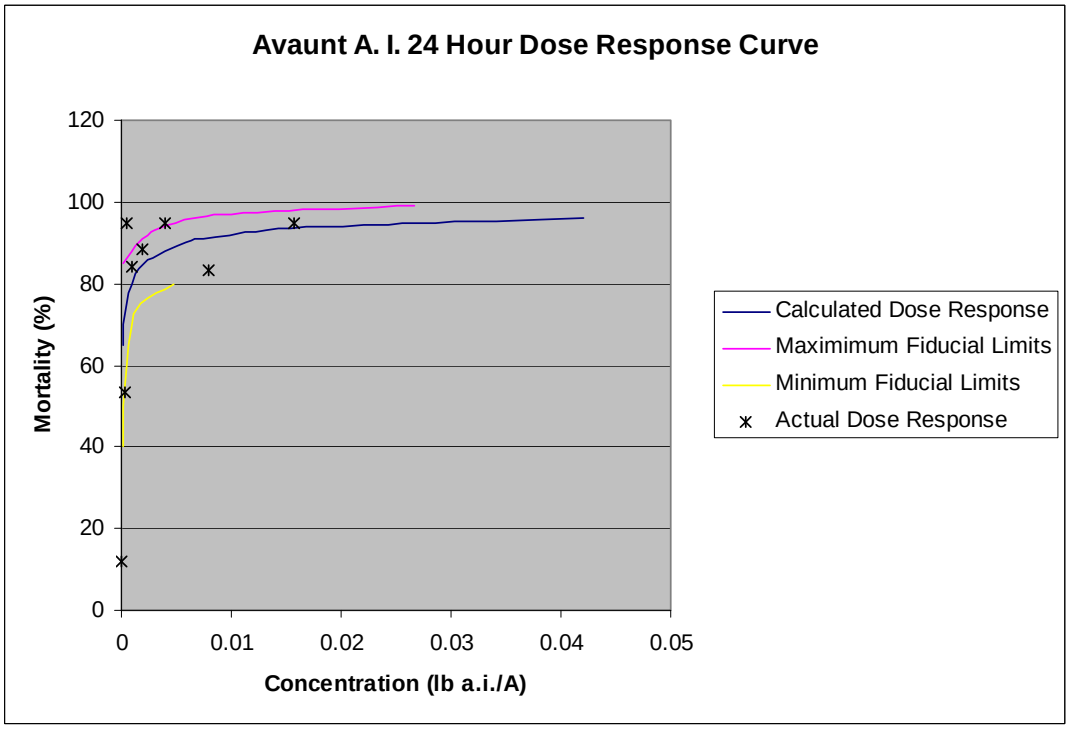

Figure A-2. Avaunt 24 hour active ingredient dose response curve.

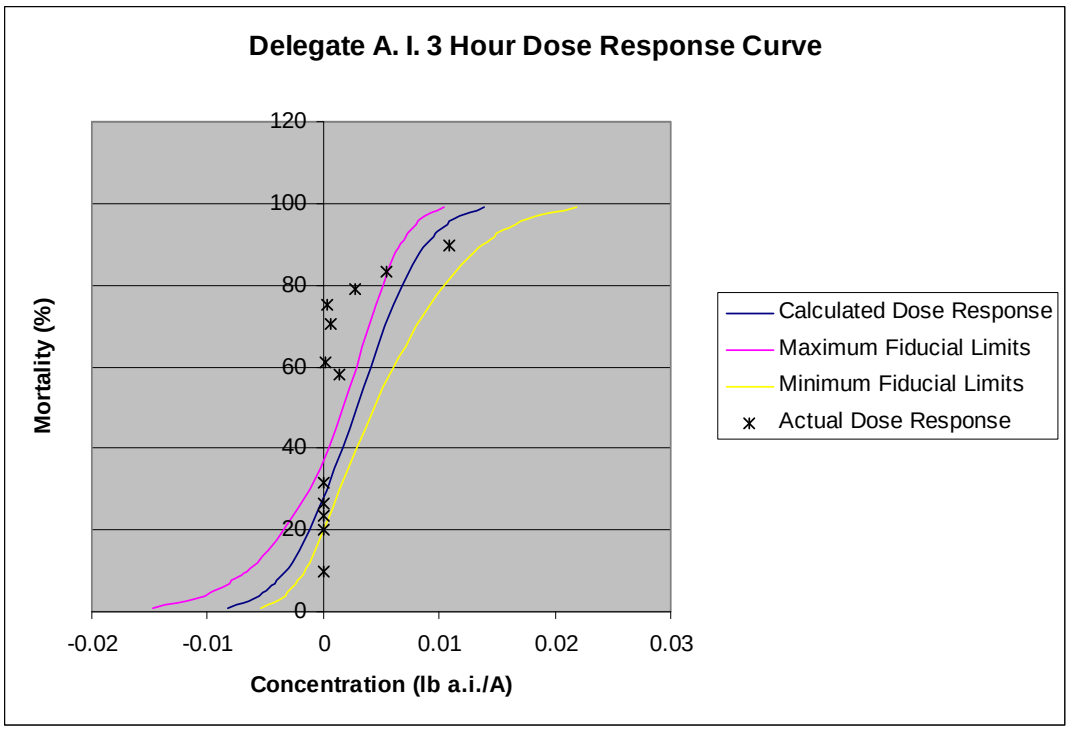

Figure A-3. Delegate 3 hour active ingredient dose response.

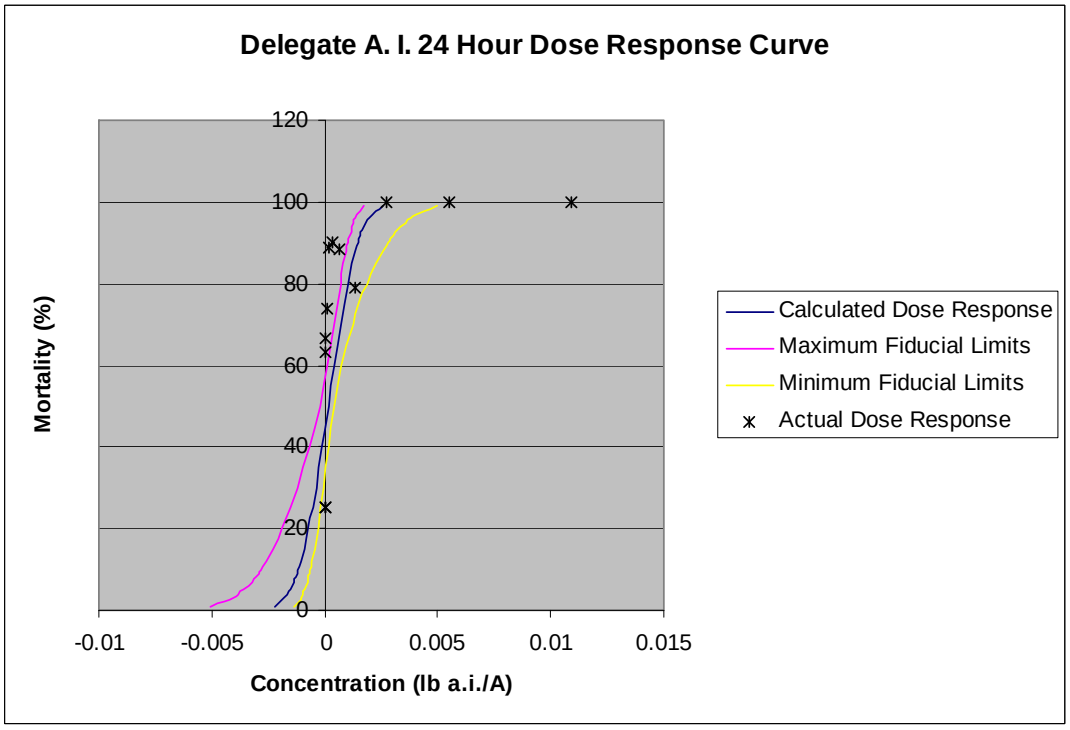

Figure A-4. Delegate 24 hour active ingredient dose response.

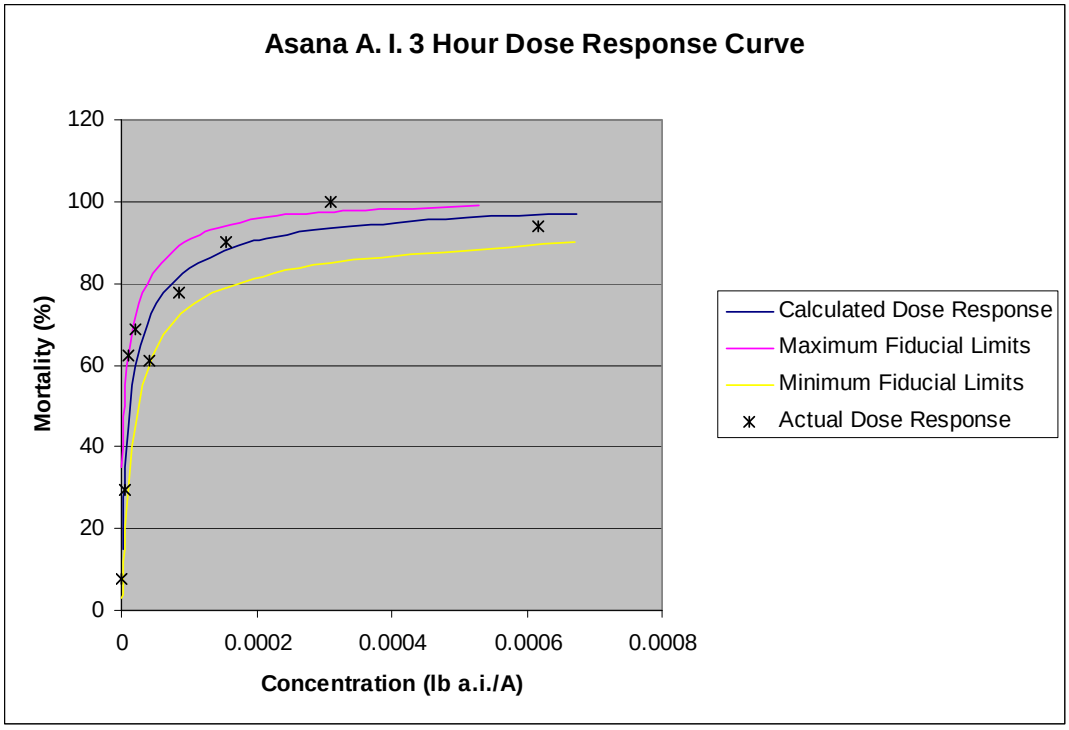

Figure A-5. Asana 3 hour active ingredient dose response.

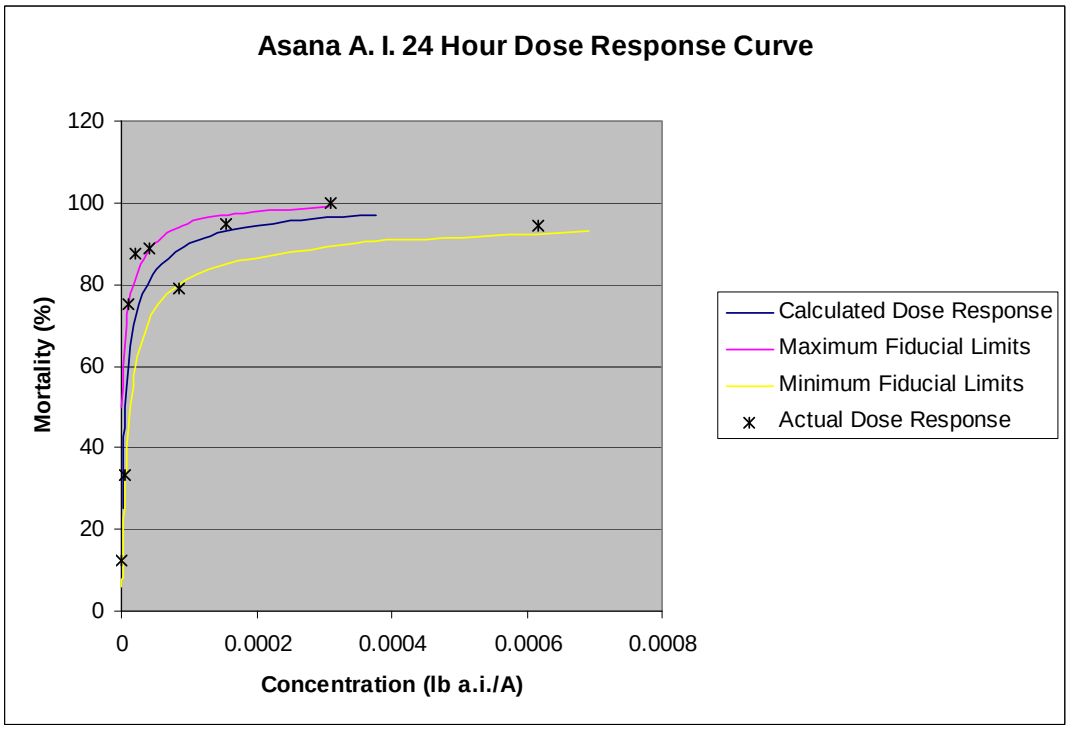

Figure A-6. Asana 24 hour active ingredient dose response.

APPENDIX B.
Lt_{50} Data Figures.

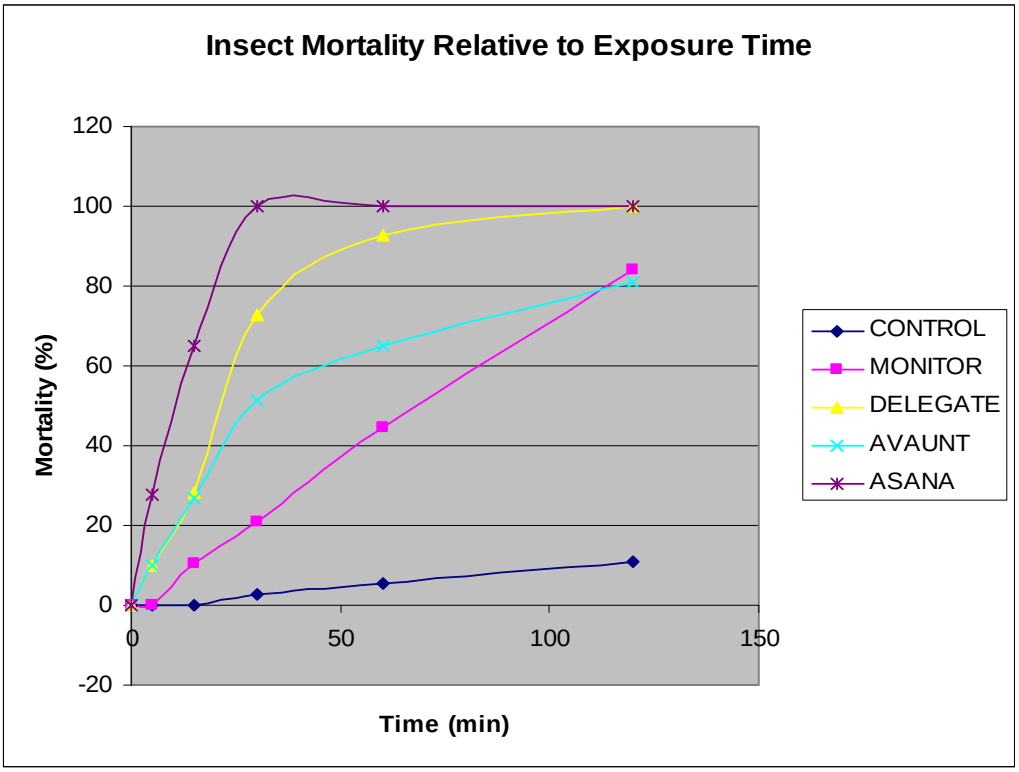

Figure B-1. Insect mortality relative to time of exposure.

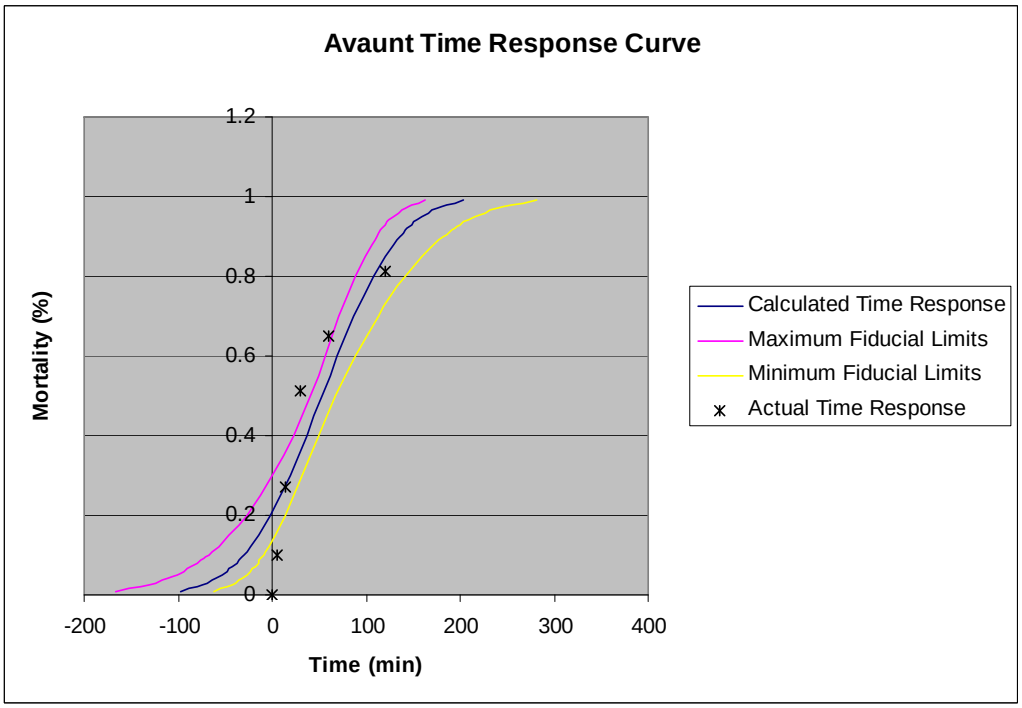

Figure B-2. Avaunt LT data.

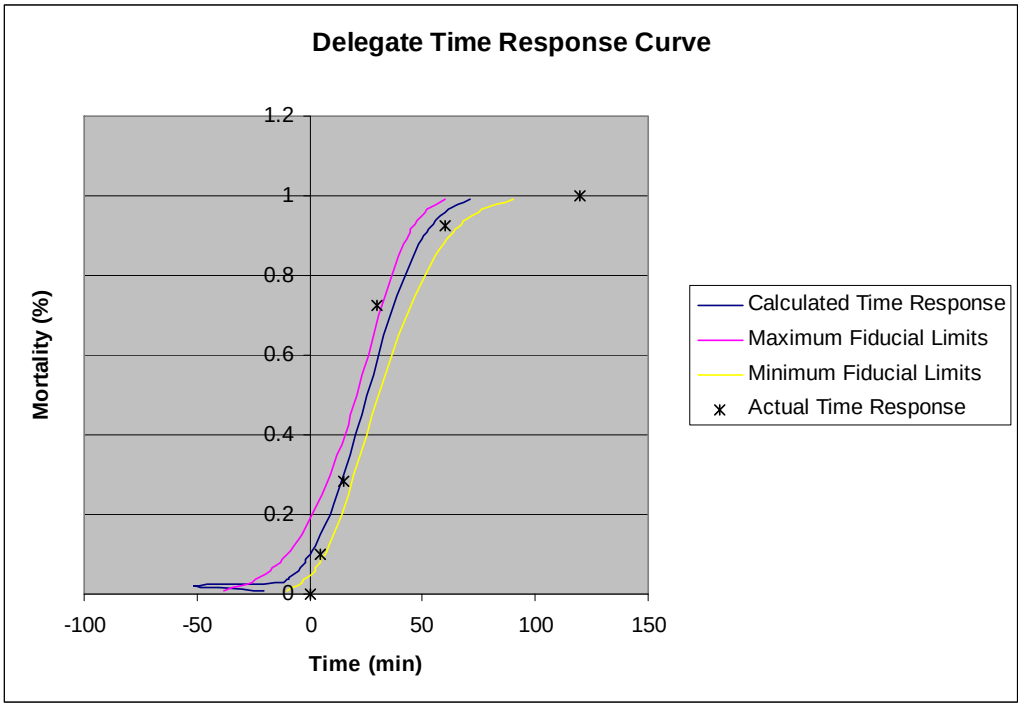

Figure B-3. Delegate LT data.

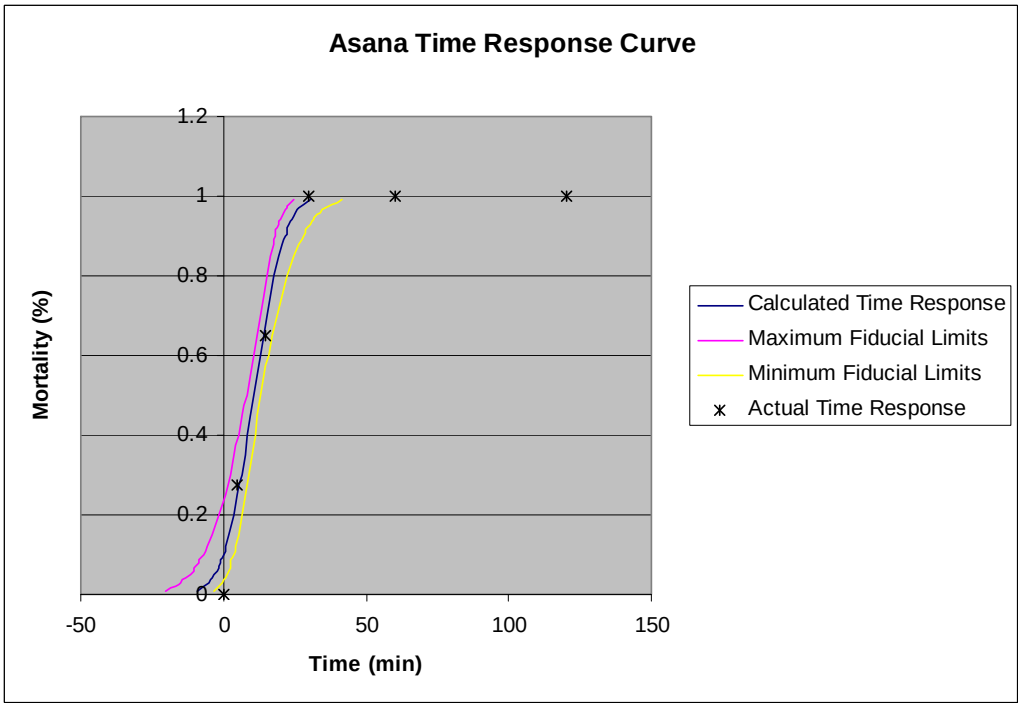

Figure B-4. Asana LT data.

APPENDIX C.
Persistence Figures.

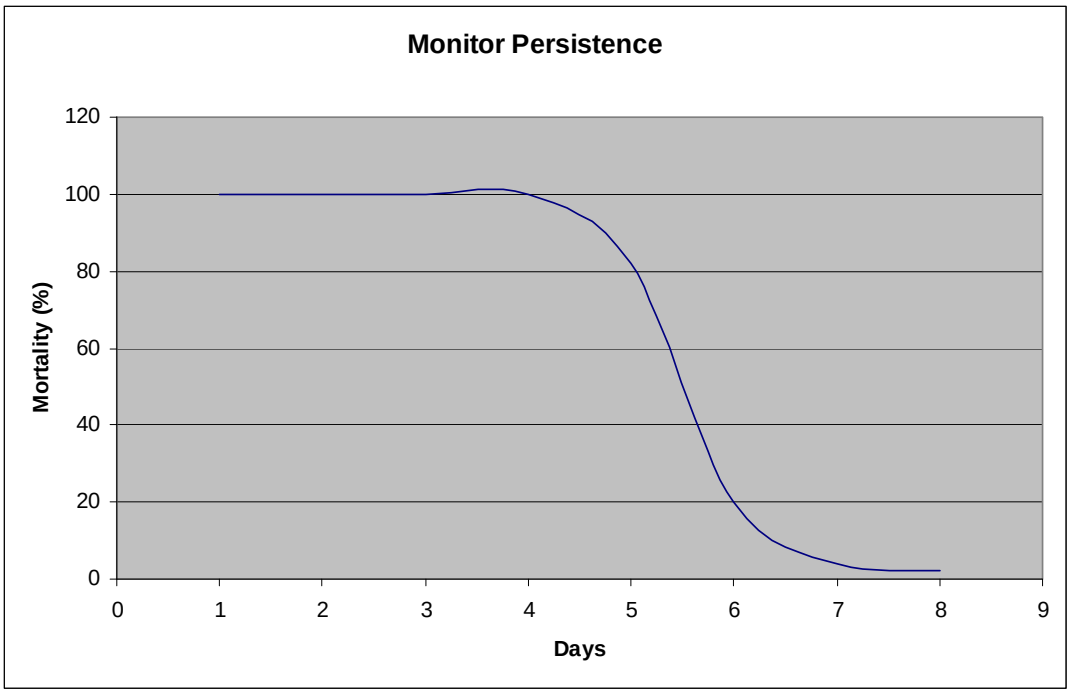

Figure C-1. Monitor persistence data (14 days after application). Half life 0.7-0.9 days (Evaristo and Casadei de Baptista 2002).

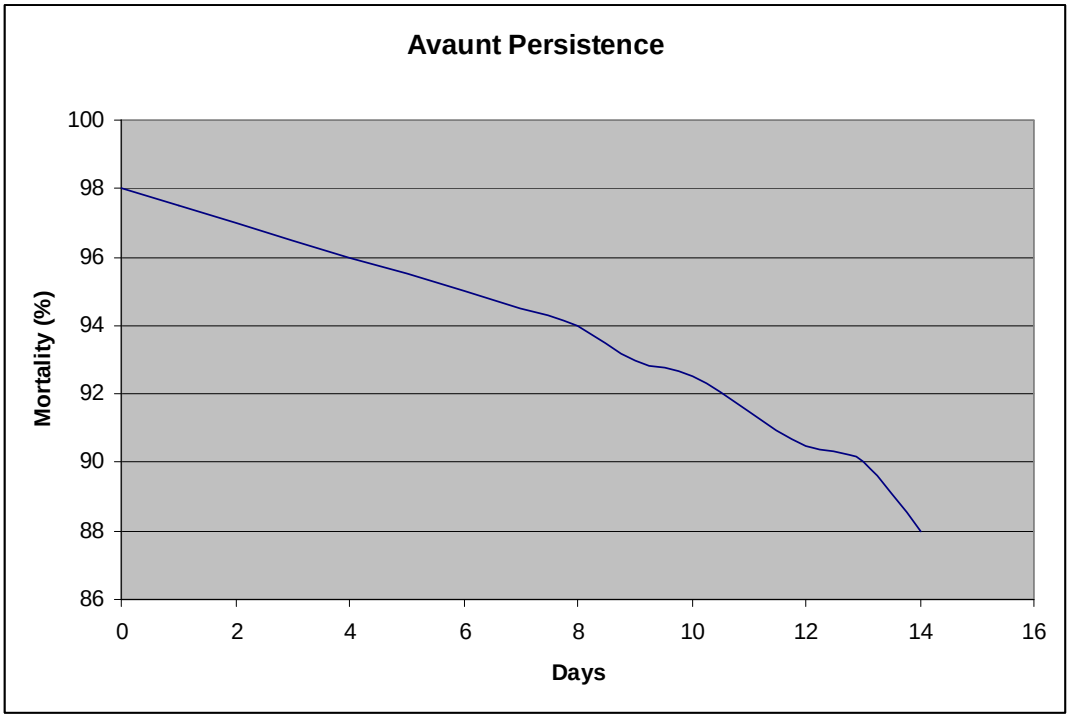

Figure C-2. Avaunt persistence data (14 days after application). Half life 3.0-3.8 days (Saimandir, J. 2009).

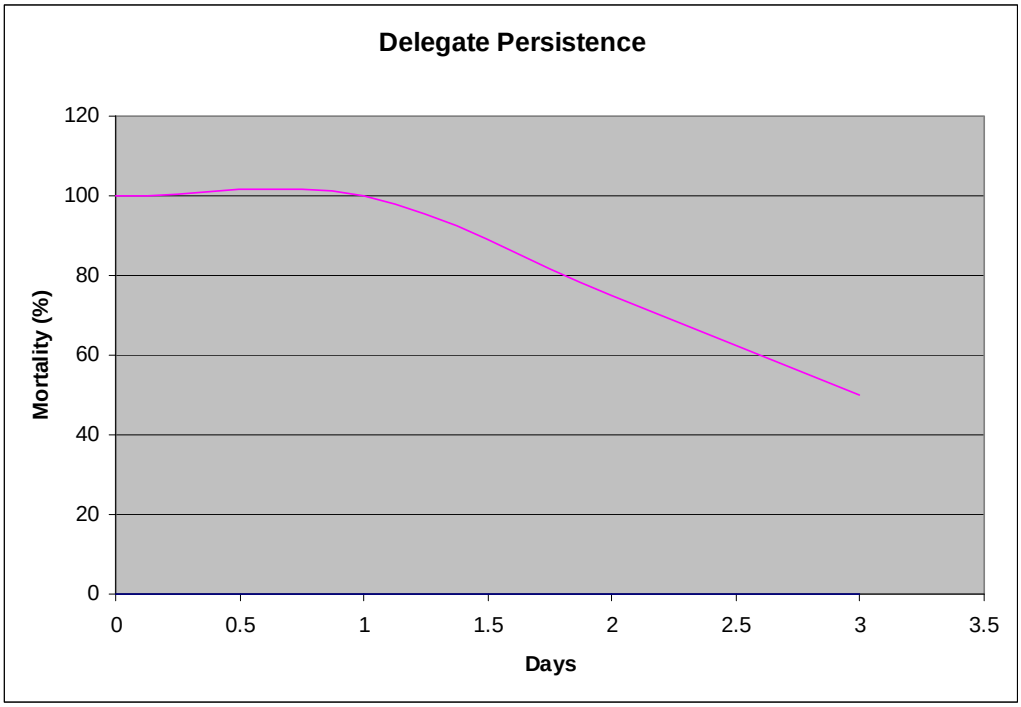

Figure C-3. Delegate persistence data (14 days after application). Half life 8.0 hours (Australian Pesticides and Veterinary Medicines Authority 2008).

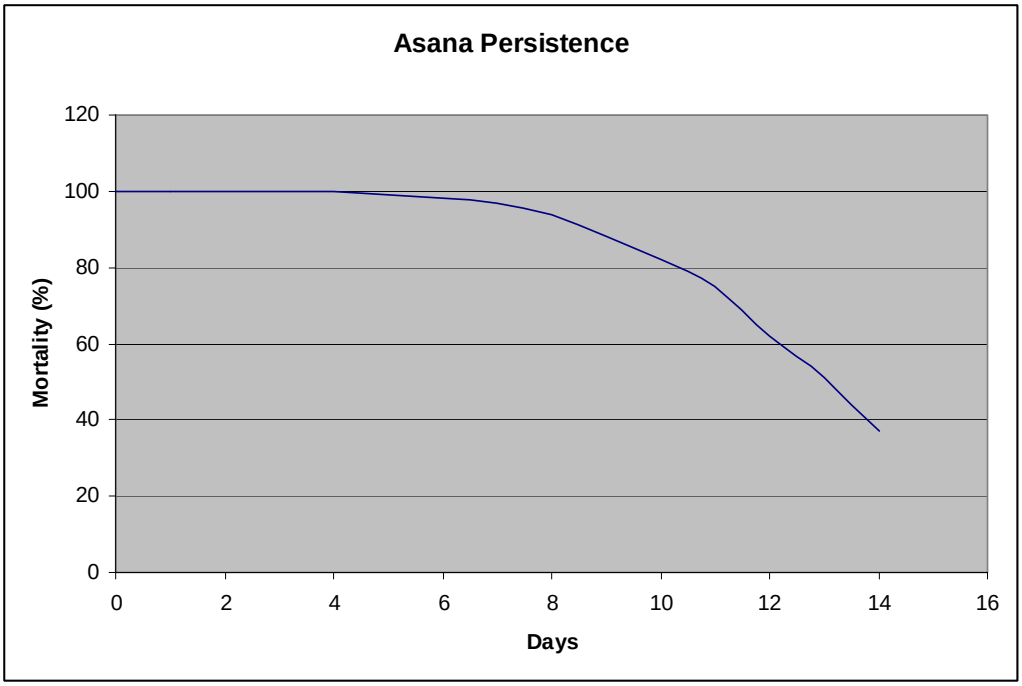

Figure C-4. Asana persistence data (14 days after application). Half life 1.0-1.6 days (Antonious 2002).