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Terrestrial Field Dissipation Studies
Purpose, Design, and Intergration

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Field Studies of Imidacloprid Distribution Following Application to Soil Through a Drip Irrigation System

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Both surface and subsurface drip irrigation can reduce overland flow and thereby reduce surface transport of pesticides. Little is known, however, about leaching of pesticides when applied via drip systems. A series of experiments were conducted over several years to characterize the horizontal and vertical distribution of imidacloprid [1-[(6-chloro-3-pyridinyl)methyl]-N-nitro-2-imidazolidinimine] in an experimental hop yard under subsurface drip irrigation. The insecticide was applied once by injection directly into the irrigation pipe buried 45-60 cm deep on each side of a hop vine row. Water exited the pipe through labyrinth emitters spaced at 90-cm intervals. Soil profiles of either 105 cm or 150 cm in depth were collected at various times following chemigation to characterize imidacloprid distribution in successive 15-cm soil layers. Imidacloprid residues were

mostly confined to soil profiles collected within a 30-cm radial distance from an emitter. When irrigation occurred on a 4-h daily time schedule (treatment 4H), imidacloprid leached to the lowest depths sampled (105 or 150 cm). Imidacloprid leaching was comparatively less extensive in two of the three trials that studied irrigation scheduling triggered on and off by soil moisture sensors recognizing pre-defined soil matric potentials (irrigation treatment MP). Pseudo-first order half-lives of imidacloprid ranged from 18 d in 4H treatments to 31 d in MP treatments. All dissipation rates were faster than previously reported for field studies at other locations. The effect of analyzing duplicate profile samples individually rather than analyzing them as bulked composites was investigated in a randomized treatment design experiment. Individual analyses of replicate plot duplicates significantly lowered the overall treatment mean standard deviation, suggesting an improved potential for resolving differences in residue distributions that may result from changes in irrigation management practices.

To improve efficiency of water use and reduce soil erosion, growers in semi-arid regions are increasingly foregoing furrow systems in favor of surface (DI) and subsurface drip irrigation (SDI). Drip irrigation is the application of water through emitters spaced at defined intervals in pipes that are placed either on the soil surface or buried below the surface. In California and the Pacific Northwest (PNW), drip irrigation is used on about 0.2 million hectares. About 20,000 hectares are drip irrigated in Washington State (*1*). DI and SDI are commonly used in perennial crops, e.g., orchards, vineyards, and hop yards, but many agronomic crops (e.g., corn, cotton) and horticultural crops (e.g., tomato, asparagus) also use drip irrigation (*2*).

The growth of interest in SDI is commensurate with its purported advantages which include: increased water use efficiency, enhanced plant growth and yield, reduced salinity hazard, decreased energy requirements, improved cultural practices, limited weed growth, elimination of surface runoff, and improved application of fertilizer and other chemicals (*2*,*3*).

Using irrigation systems to apply fertilizers and pesticides is commonly referred to as chemigation. Chemigation via DI and SDI (i.e., drip chemigation) also has advantages compatible with environmental stewardship: no worker exposure to foliar pesticide residues, reduction of waste from cleaning out spray tanks, elimination of drift, and less exposure of biological control organisms to pesticides in integrated pest management programs. Systemic pesticides seem particularly well suited for application by drip chemigation and would be

compatible with IPM if plant uptake was rapid enough to allow delay in application until a pest problem was developing.

Despite the advantages of drip irrigation systems, further expansion of drip irrigation technology has been limited by several concerns: costs of implementation, difficulty of laying pipe in certain soil types, management of blocked emitters, and the lack of enough data to convince growers that it offers a superior method of fertilizer and pesticide application.

Particularly needing solutions are questions about pesticide uptake by plants and potential leaching in soil. While the efficacy of chemigated systemic insecticides seems adequate, especially for sucking insect control, plant uptake kinetics will determine if applications can be made in an emergency rather than made prophylactically. Also, residues in harvested commodities should be substantially less than the tolerance levels, and preferably minimized to reduce dietary exposure.

The effects of DI and SDI on leaching of pesticides injected into water and emitted as point sources into the soil, as opposed to leaching by water after application directly to the soil, has hardly been studied, especially under field conditions. Such leaching concerns are prompted by studies showing chemicals applied in flood irrigation water can leach to greater depths than chemicals applied directly to the soil surface (*4*). Chemicals have also been observed to rapidly leach along preferential flow paths when applied with irrigation water (*5*). Studies should focus on the initial distribution of chemigated pesticides and the translocation of residues as the growing season progresses.

In addressing concerns about pesticide leaching, we monitored the distribution of imidacloprid aphicide in a hop yard following injection into an SDI system. (*6*). Imidacloprid is a comparatively low toxicity systemic insecticide with both foliar and soil bioactivity, but its high water solubility (500 ppm) and low soil distribution coefficients (*7*) suggest that it may be comparatively mobile. In our early studies, irrigation was supplied on a daily 4-h schedule (*6*). Imidacloprid residues were observed below the emitters at the maximum sampling depth of 105 cm, suggesting that fixed-schedule water delivery might promote leaching.

Observations from our earlier study led to the hypothesis that vertical movement of imidacloprid could be reduced by irrigating only when soil water content fell below an optimum matric potential. Over several growing seasons, we have conducted various field experiments to help test our ideas about best management practices for chemigation via drip systems. In an effort to further product understanding, we now report the results from several field experiments designed to determine horizontal movement around the irrigation emitters, vertical leaching under two different irrigation scheduling regimes, and the effect of sampling replication on residue variability.

Materials, Methods, Procedures

Experimental Field Location and Description

The study site was located in an experimental 1-ha subsurface drip-irrigated hop yard that was developed in 1992 at the Washington State University Irrigated Agriculture Research and Extension Center (IAREC) near Prosser, WA. The station lies in the eastern end of the Yakima Valley and receives an annual rainfall of 15-25 cm. The soil was classified as a Warden very fine sandy loam (coarse-silty mixed mesic Xerollic Camborthids), which is common in the lower end of the Yakima Valley. A composite sample from the top 60 cm had a 49% silt and 3.2% clay content, a 1.03 % organic matter (OM) content, and a pH of 8.0. Soil collected between 60 cm and 105 cm had a pH of 7.8, an OM content of 0.74 %, and a silt and clay content of 48% and 5.2%, respectively. Gravimetric soil water content (w/w) at 33 kPa (moisture holding capacity, MHC) in the top 60 and lower 60 cm of the sampled profile was 18.7 and 18.1%, respectively.

The yard was planted with four varieties of hops (Chinook, Willamette, Columbus, and Mt. Hood) laid out in four 0.2-ha blocks (Figure 1). Each block was divided into 12 separate plots, each with 5 rows spaced approximately 2.1 m apart and consisting of 7 hop vines in hills, also spaced 2.1 m apart. Each row was irrigated via one subsurface polyethylene pipe (1.32-cm ID) buried approximately 45-60 cm deep. Each pipe ran parallel to the hop rows and was placed within 60 cm of the north side of each row. The pipe was fitted with labyrinth emitters spaced 90 cm apart. The labyrinth consisted of a small plastic insert molded into a series of circuitous channels in which water moving down the central pipe opening could enter and exit through a tiny hole to the outside of the pipe. Water was emitted at a rate of 1.9 L/h (~1 mm/h).

Irrigation Scheduling

Each of the 12 plots within a variety block could be independently irrigated and chemigated (Figure 1). A 12-valve manifold sat at the top of the yard. Water was pumped into the manifold from a well. Each of the 12 lines contained an injector port for application of pesticides or special fertilizer treatments. Normally, all the blocks were fertigated uniformly (140 kg/ha N; 28 kg/ha P). Irrigation scheduling was controlled either through a timer or through feedback from buried soil water sensors installed in the center of each variety block (1996-1998) or in individual plots (1999) (Figure 1). Two types of sensors—frequency domain reflectometers (FDR, Campbell Scientific 615L)

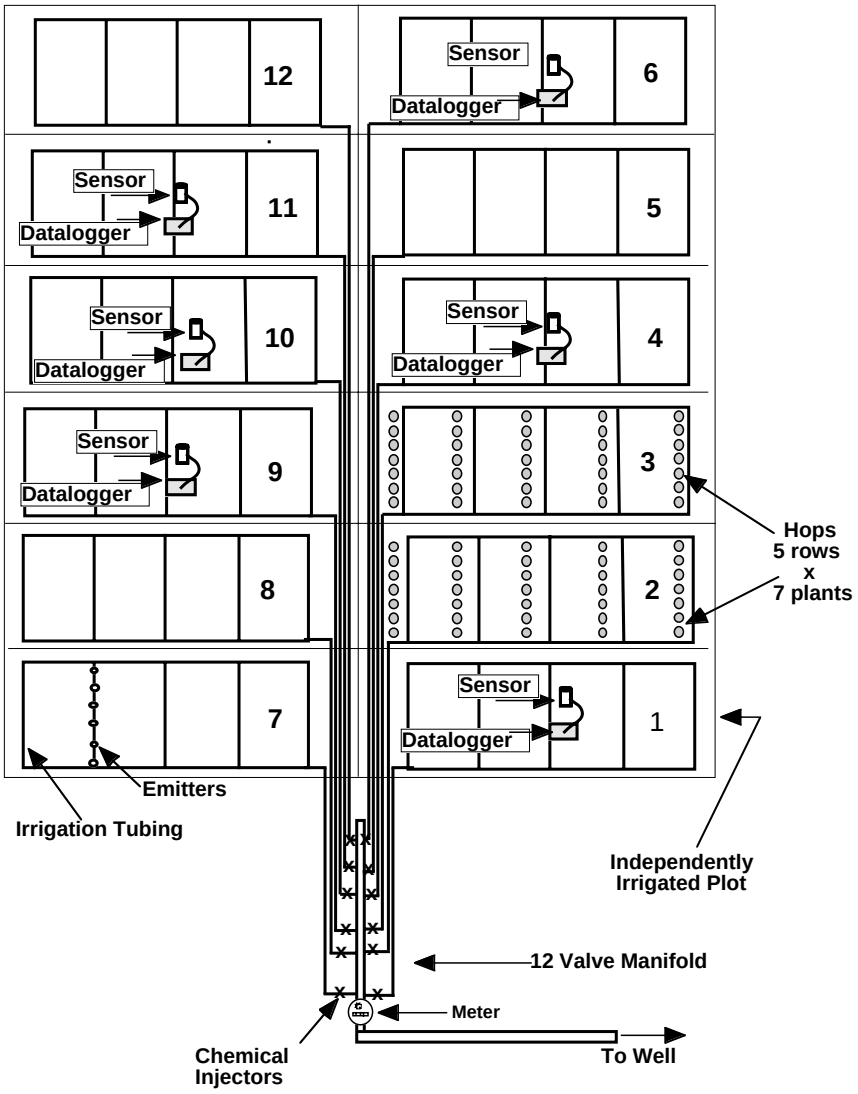

Figure 1. Schematic of a 0.2-ha variety block consisting of 12 independently irrigated plots in the experimental drip irrigation hop yard at WSU-Prosser.

and standard tensiometers—were buried at a depth of ~40 cm and connected to a datalogger (Figure 1). During 1996, water was automatically turned on for 4 hours daily (treatment **4H**). During 1997-1999, water turned on when soil

matric potential dropped to -15.5 kPa and turned off when matric potential reached -14.5 kPa (treatment **MP**).

Horizontal and Vertical Distribution of Imidacloprid—Fall 1996

We previously reported observations of the horizontal and vertical distribution of imidacloprid within a 30-cm radius of the emitters during June through August of 1996 in variety block Willamette (*6*). In September 1996, just prior to harvest of the hop cones but when the plants were going into senescence, we repeated the study on a previously untreated plot of hop variety Willamette. Distribution of imidacloprid was monitored for an eight day period to confirm earlier observations and determine possible horizontal movement of imidacloprid beyond 30 cm.

Prior to application, the emitters were located by exposing the pipe at each end of the plot. A field tape measure was laid as a transect between the exposed emitters, and the locations of the remaining emitters were located at 90-cm intervals along the transect and delineated with flags for later sampling.

After the emitters were located, imidacloprid (formulated as Provado) was mixed in water and injected by a peristaltic pump into the irrigation system through a manifold that led to separate irrigation lines for each plot within a variety block (Figure 1). The lines were flushed for 30 minutes with water following insecticide injection. The rate of application was 0.28 kg AI/ha.

To determine the horizontal and vertical distribution of imidacloprid, a series of soil samples were taken to a depth of 105 cm at various distances from the emitter in a pie-shaped distribution (Figure 2). We also took profile samples at a 45-cm distance from the emitter along the direction of the pipe and in a 45-cm distance perpendicular to the emitter in the direction of the interrow area. Nine profiles were collected on days 1, 3, and 8 after application.

Soil samples at each numbered location (Figure 2) were collected in successive 15-cm depths using a bucket auger (5-cm diameter). The top and bottom 2.5 cm of each depth were removed to avoid cross contamination between layers and from surface soil that may have fallen into the bore hole. Between samples the bucket auger was brushed in water and then dried before taking the next sample. Samples were held in double polyethylene bags, returned to the lab, and stored at –20 °C until analyzed.

During July and August of 1997, approximately 10 months after application, replicate soil cores were collected from the plot treated the previous September. A single profile was sampled within 15 cm of the emitter using a 10-cm diameter bucket auger. The soil was again sampled in 15-cm increments, discarding the upper and lower 2.5-cm of soil. Soils were held in storage until analysis as previously described.

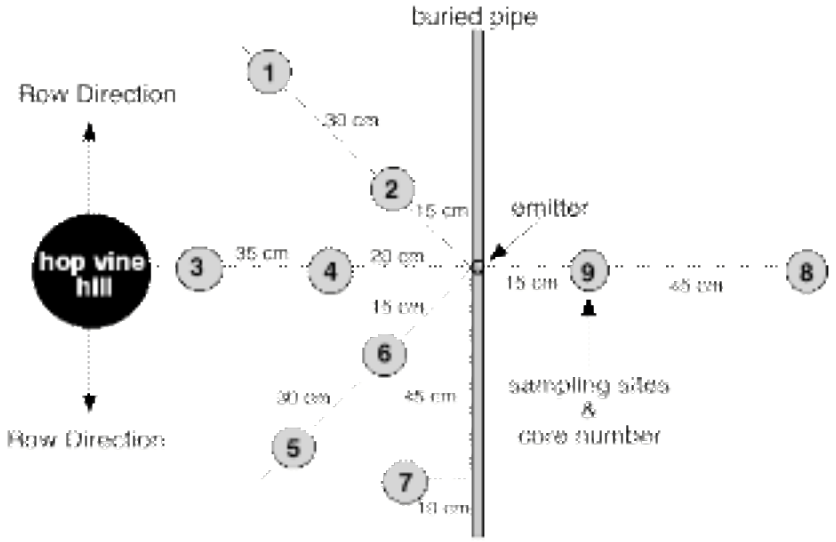

Figure 2. Sampling scheme for soil profiles around the buried emitters. Each numbered circle represents a soil core taken to a depth of 105 cm. Distances along the dashed transect lines represent the length between the marked location of the emitter and the center of each profile.

Vertical Distribution of Imidacloprid with Irrigation Under Matric Potential Control (1997-1999 Field Studies)

During 1997 and 1998, variety Willamette plots that had been treated during the early summer of 1996 were retreated with 0.28 and 0.22 kg imidacloprid/ha, respectively. Insecticide application occurred after the emitters were located as described for the September 1996 experiment. Irrigation water was turned on automatically whenever soil matric potential dropped below –15.5 kPa. A single FDR was buried at a depth of 40 cm in the center of the variety block to control the irrigation scheduling and shut off the water when the matric potential rose to –14.5 kPa.

Soils were sampled just prior to application and seven times later over the next 70 days. Each collection consisted of two randomly chosen locations, one each in rows two and four of the plots. The profile was started within 15 cm of the emitter on the hop row side. Soil was collected with a 10-cm diameter bucket auger in 15-cm layers to a depth of 150 cm. Soils were handled as previously described.

During 1999, studies were switched to variety block Chinook using plots that had not been treated with imidacloprid for at least two growing seasons. Replicate plots were delineated to compare two irrigation schedules simultaneously—4H and MP. FDR instrumentation and tensiometers were moved to the center of each replicate treatment plot (Figure 1). After application of imidacloprid (0.22 kg/ha), soil was collected several times over the next 2 months and handled as described for the 1997-98 experiments. Two randomly chosen profiles were collected from the second and fourth row of each of the replicate treatment plots, making a total of four profiles sampled per treatment. Within two weeks of application, however, it was discovered that one of the MP replicate plots had not actually received an insecticide application. At this point an extra profile was collected from its corresponding replicate on the remaining sampling days.

Sampling Variability Experiment

During June 2000, imidacloprid distribution experiments were moved to variety block Mt. Hood using plots that had not been treated during the previous two growing seasons. Soil moisture monitoring instrumentation was set up as previously described for the 1999 experiments. To achieve the objective of better quantifying imidacloprid distribution following application and characterizing sampling variability, three replicate plots were each delineated for irrigation treatment 4H or MP. Following imidacloprid injection (0.22 kg/ha), soil samples were collected within 24 h and 7 d later.

Analytical Methods

During 1996-1998, soils were mixed by hand prior to removing a sample for analysis. Owing to the low water content of the soils and the lack of structure (due to low clay and organic carbon content), it was not necessary to sieve the soils. To characterize the variability of laboratory subsampling, six 20-g subsamples were removed from each of five previously collected field samples having average concentrations ranging from 2-640 ng g^{-1} (ppb) The coefficient of variation (CV) for recovered residues ranged from 12%-39% (mean = 25%). To minimize variation in laboratory subsampling further, soils collected during 1999 and 2000 were laid flat on paper, mixed back and forth, and then approximately one-quarter of the total was removed for laboratory analysis and long-term storage (~-20°C). The more extensive mixing did not appreciably reduce the CV for subsampling.

Soils were thawed for 24 hours at ~6°C for 24 h prior to analysis. Ten grams of soil were removed to determine % moisture (w/w). Thirty grams of soil were weighed into centrifuge bottles and extracted twice by reciprocal shaking with either 50 mL of water (1996 samples as described in *6*) or a 9:1

mixture of acetonitrile (ACN) and deionized water (1997-1999). In 2000, 0.01M $CaCl_2$ was substituted for water. After each extraction, samples were centrifuged for 10 minutes and the supernatant was filtered under vacuum through Whatman 934H glass microfiber filters. The acetonitrile was removed by vacuum rotary evaporation. The remaining water from the 1996-97 extracts was partitioned twice with 75 mL of CH_2Cl_2 and then further processed as described in *6*. The resulting water extracts for the 1998-2000 samples were passed through a Bakerbond C18 SPE 6-mL cartridge. Imidacloprid was eluted from the cartridges with two 4-mL aliquots of ACN. The ACN was evaporated to dryness under nitrogen in a water bath (60 °C), and then the extract was reconstituted in 1 mL of 1:1 ACN:water. All finished extracts were passed through a 0.45-µm Acrodisc filter and stored in brown 1.8-mL vials for HPLC.

Imidacloprid was detected and quantified on a Varian HPLC using a 4.5-mm x 15-cm C18 reversed phase column. Imidacloprid was eluted using a program gradient of 95:5 ACN:H_2O to 100% ACN over a 20-min period. Imidacloprid was detected with a photodiode array detector set to monitor absorbance at 268 nm. The spectral analysis mode was used as necessary to qualify questionable peaks eluting at the expected retention time for imidacloprid. Based on the ability of the detector to produce a reliable signal above background when 60 µL of a 0.03 µg mL^{-1} calibration standard was injected, the method detection limit was set at 1 ng g^{-1} (1 ppb) oven dry soil.

Every day that field samples were extracted, one or two aliquots of soil collected from an untreated plot were freshly amended with imidacloprid to yield a concentration of 50 ppb. Extraction efficiency over the four years of the reported studies was 90% or greater with a CV less than 15%.

Results and Discussion

Horizontal and Vertical Distribution of Imidacloprid—Fall 1996

One problem we encountered was determining where to sample a soil profile relative to the location of the emitter. Because published observations of water patterns around drip emitters showed a radial distribution with decreasing water potential as distance from the emitter increased (*8,9*), we hypothesized that imidacloprid would stay comparatively close to the emitter along any horizontal direction. We also assumed that imidacloprid distribution around the emitter would be homogeneous so that a sample taken on any side of the pipe would be representative. During the 1996 summer studies, imidacloprid was found within 7 days of application to be distributed in all five cores taken within a 30-cm radius of the emitters (*6*). Cores taken closest to the emitter did not necessarily have the highest concentrations of imidacloprid.

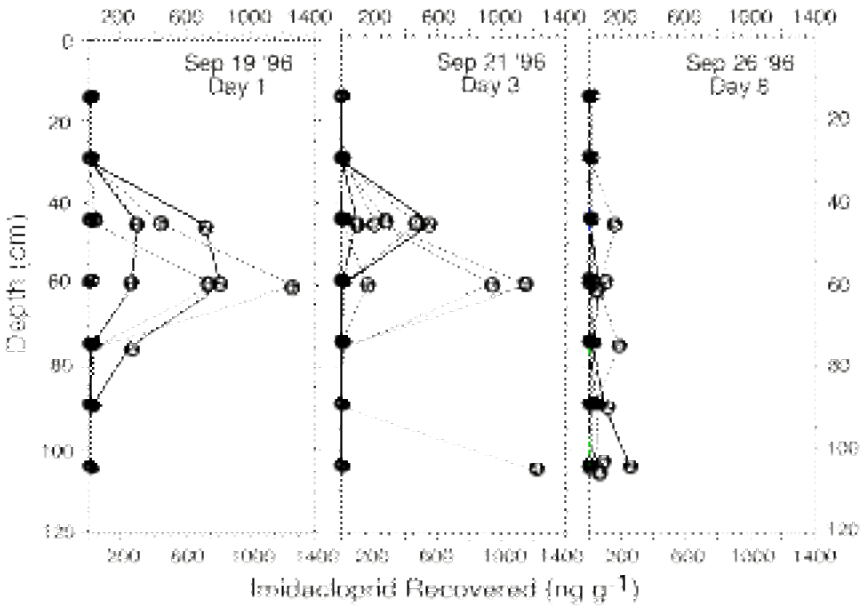

Figure 3. Recovery of imidacloprid residues in cores within a 45 cm radius of a drip irrigation emitter following application on September, 18, 1996. Refer to Figure 2 for location of core numbers relative to emitter position.

During the fall 1996 experiment, imidacloprid was generally found in the injection zone (45-60 cm) at the highest concentrations in the cores within 15-20 cm of the emitter (Figure 3, cores 2, 4, 6 on day 1). This pattern was also exhibited on day 3. By day 8, imidacloprid concentrations had significantly declined in all cores but continued to be detected at a radial distance of 30 cm. Imidacloprid was never detected in core 9 that was located 45 cm from the emitter on the north side of the irrigation pipe.

Imidacloprid residues were not detected below 75 cm the day after application, but >1000 ppb was detected in core 4 at the lowest sampling depth (105 cm) on day 3 (Figure 3). By day 8, imidacloprid was detected throughout the profile, but its rapid dissipation suggested leaching below the sampling zone. Soil moisture (data not shown) at the lower depths did exceed the moisture holding capacity in some cores, suggesting saturated flow and consequently, enhanced mobility. During the fall, the hop plants are unlikely to need much water, so a daily four hour irrigation was likely excessive.

To test the hypothesis of leaching below the sampling zone, during July and August of 1997 replicate cores were sampled to a depth of 150 cm at a distance

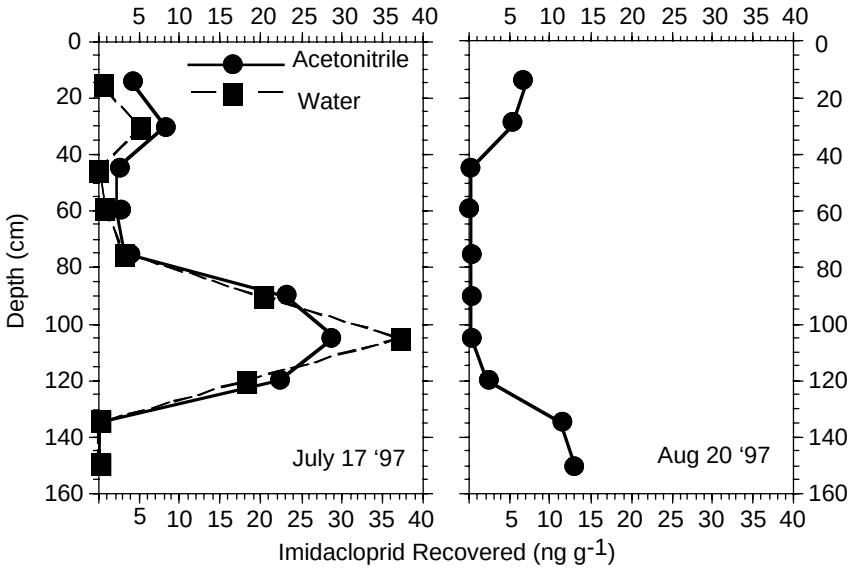

Figure 4. Distribution of imidacloprid residues in soil treated during Sept.'96.

of 15 cm from the emitter. Replicate soil samples were extracted with either water (as described in *6*) or with 9:1 ACN:water. Imidacloprid residues were observed in cores collected 10 months after application at a depth of 120 cm (Figure 4). Although residues had plenty of time to "age", both water and ACN extracted similar amounts of imidacloprid.

Other research has suggested that with increasing incubation times in soil, the soil distribution coefficient of imidacloprid increases, making water a comparatively poorer extracting solvent (*10,11*). If aged residues are less available to extraction by water, than soil mobility may also be allayed. While our past work also suggests an aging effect for field-collected imidacloprid residues (*6*), water was still an efficient extracting solvent. ACN extraction of duplicate cores collected 11 months after application indicated further leaching of "aged" residues to a depth of 150 cm (Figure 4). The residues observed in the uppermost layers of the profile may represent translocation in water that sometimes wetted the soil surface, presumably when the soil became saturated in the vicinity of the emitters.

Vertical Distribution of Imidacloprid with Irrigation Under Soil Matric Potential Control (1997-1999 Field Studies)

The deep leaching of imidacloprid significantly below the emitter zone with daily 4-h irrigation led to an examination of alternative irrigation scheduling as a best management practice. Many growers automatically irrigate using a set schedule each day during the hottest periods of the summer, which occur during July and early August in south central Washington. However, growers are increasingly interested in matching water utilization with crop needs. Thus, if the optimal moisture content for crop growth was determined, then water could be turned on and off in pulses to keep the soil moisture in this range. The problem with deployment of this strategy is determining the most efficient placement and appropriate number of soil moisture sensors.

During 1997 and 1998, we determined the distribution of imidacloprid in soil cores with irrigation controlled by feedback from soil moisture sensors located in a central position in an entire 0.2 ha block. During 1997 (Figure 5), imidacloprid remained in its injection zone one week after application, moved to a depth of 105 cm (22 ppb recovered) within 23 days, but dissipated from this depth by day 43 and day 75 (data not shown) after application. During 1998 (Figure 5), in contrast, imidacloprid was recovered at 90 cm on day 21 (95 ppb) and on day 42 (65 ppb). At 75 days in both years, imidacloprid was found in the deepest soil layers, but residues were also found at this depth in pre-application samples (Figure 5, Day -1). The plot had been treated for at least four years in a row, and residues had not completely dissipated.

Low levels of imidacloprid from previous growing seasons seemed mobile and significant amounts were still extractable in water (data not shown). A published experiment on aphid control in the same plots also showed that the low ppb levels of imidacloprid may still be bioavailable (12). For example, significant aphid control occurred in insecticide-untreated plots during 1997 if the plots had been chemigated with imidacloprid either one or two years before. Untreated plots without past imidacloprid injections had significantly more aphids (12).

During 1999, we monitored imidacloprid distribution under both 4H and MP irrigation schedules simultaneously within a replicated plot design. To avoid the confounding factor of imidacloprid residues from a previous years application, experiments were moved to variety block Chinook in 1999. Plots were chosen for study if imidacloprid had not been used for at least two or more years. Soil moisture sensors were placed within the center of each replicate treatment plot.

Recoveries of imidacloprid were similar 24 hours after application (~700 ppb) (Figure 6). By day 15, imidacloprid remained around the injection zone in the MP treatment but was detected at the 90-cm depth in the 4H treatment. By day 28, some wetting at the soil surface was noted and imidacloprid was recovered in the top 30 cm. After two months, imidacloprid residues in the MP

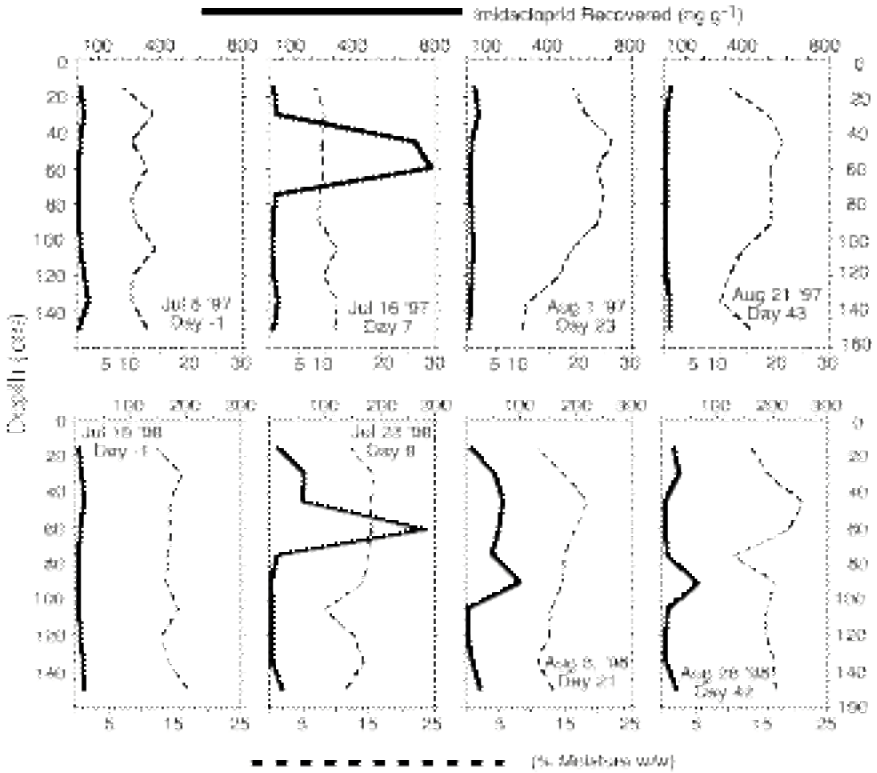

Figure 5. Soil profile distributions of imidacloprid under irrigation controlled by soil matric potential during 1997 and 1998.

treatment were mostly recovered from the injection zone and above but had moved to the 120-cm depth in the 4H treatment.

During the first month after application, gravimetric moisture content analysis suggested that soils in the emitter zone of both irrigation treatments were near or above MHC (Figure 6). Pertinently, water pulsed on and off in the MP treatment, possibly allowing some drying to occur and retardation of imidacloprid leaching. At two months post application, moisture content exceeded MHC in the 4H plot at the 90-cm depth, suggesting a greater potential for enhanced leaching of imidacloprid below this level. Coincidentally, at depths ≥90 cm, nearly 20 times more imidacloprid was found in the 4H profiles than was found in the MP profiles (Table 1). However, nominally more imidacloprid was found below 90 cm in the MP profiles during the 1997 and 1998 growing seasons than was found in the 1999 growing season (Table 1). On the other hand, the cumulated concentration in the 1997 MP profiles was still nominally less than in the 1999 4H profile.

Figure 6. Imidacloprid distribution in soil under two irrigation management schedules, 4-hour daily (4H) and matric potential control (MP).

Table I. Estimates of First-Order Half-Life for Dissipation of Imidacloprid and Cumulative Residues (ppb) Recovered at a Depth ≥90 cm

Year	*Irrigation Control*	*First Order $T_{1/2}$ (days)*	*R^2*	*Cumulative Residue @ ≥90 cm*
1997	Matric Potential	21.9	0.73	15
1998	Matric Potential	29.9	0.77	60
1999	Matric Potential	30.9	0.87	4
1999	4 Hour Daily	17.6	0.73	73

Owing to the comparatively high water solubility of imidacloprid, concerns have been expressed about its leaching potential. These concerns have been allayed, however, by laboratory studies showing increases in soil distribution coefficients with decreases in concentration and decreases in mobility with residue aging (*7,10,11*). Field studies also indicated less mobility than the water solubility would indicate (11). In contrast, we showed that under irrigated conditions with subsurface applications, imidacloprid moved beyond the injection zone to depths of 150 cm. However, after drip chemigation from surface emitters in a commercial hop yard, imidacloprid remained in the top 90 cm of the soil profile through harvest (13). As shown in our 1999 experiments, control of irrigation scheduling by soil matric potential monitoring and feedback can also prevent leaching of imidacloprid in subsurface systems.

Another important consideration for determination of leaching potential is residue persistence. To determine how quickly imidacloprid dissipated from the soil profiles, the bulk density and mass of soil collected in each 15-cm layer were assumed to be constant so that concentrations could simply be added. The concentration data were natural log transformed and subjected to linear regression analysis for calculation of a pseudo first order half-life (Table 1). Over the three years of the study, imidacloprid half-life in MP irrigation ranged from 21 to 30 days but was only 18 days in the 4H irrigation treatment. These half-lives are shorter than the 40-42 day half-life reported from experiments in non-irrigated sugar beets (*14,15*). In the presence of manure fertilizer, the half-life increased to about 100 days, suggesting that sorption may have affected bioavailability for microbial and plant uptake.

Most studies have shown little mineralization of imidacloprid in soil and a comparatively low percentage of metabolite recovery (*11,17*). Imidacloprid is unlikely to undergo hydrolysis under agronomic pH ranges (*16*). The influence

of plants on pesticide dissipation was clearly shown in another experiment that compared imidacloprid half-life in bare soil and in soil with a ground cover (*17*). Imidacloprid half-life decreased from 190 days in soil without plants to 45 days in soil with the cover crop. In our hop yards, imidacloprid dissipation may have been enhanced by the tendency of hop roots to grow toward the emitters, increasing the potential for uptake. In other studies we showed that uptake of imidacloprid by hop plants was very rapid after injection into the irrigation system and remained at μg g^{-1} (ppm) levels in leaves until cone harvest (*13*).

Sampling Variability Experiment

One limitation to developing best management practices for soil, water, and pesticide management is the need to compare different systems in the field and determine quantitatively their effectiveness. Our studies through 1998 were essentially qualitative in nature; either a 4H system or an MP system was studied in any one year. The 1999 studies attempted to compare systems in the same year. Thus, a replicate plot design was used but individual profiles were treated as independent experimental replicates. Nevertheless, even with three degrees of freedom, the coefficients of variation were too large to discern

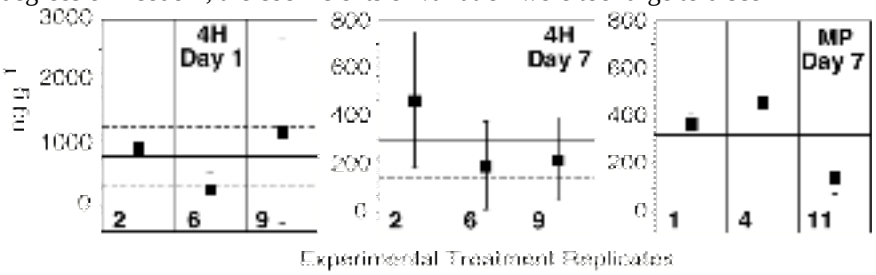

Figure 7. Mean (squares) and standard deviation (vertical lines) of imidacloprid residues recovered in the combined 45- and 60-cm depths for individual duplicate cores collected in each replicate plot of irrigation treatments 4H and MP. Bold horizontal lines represent the overall treatment means and dashed lines represent the overall treatment standard deviations.

statistical differences between residues recovered from any depth on any day of sampling. In an attempt to overcome this limitation, sampling replication was increased during the 2000 growing season.

Three replicate 4H and MP plots were delineated in a randomized design. Two randomly selected cores were collected per replicate plot. Normally, duplicate cores are bulked together before analysis in an effort to save resources. We decided to analyze the 45- and 60-cm layers from each core separately, effectively doubling the number of samples to process. A similar sampling

strategy was deployed in a previous field study of waste herbicide dissipation in soil following different application treatments (18).

Although the experimental protocol called for allowing the irrigation lines to flush for 30 minutes following application, the lines leading to the MP plots were inadvertently shut off shortly after injection. Thus, samples collected within 24 hours after application failed to contain imidacloprid residues. Samples collected seven days after application, however, did have residues at levels approaching 500 ppb.

The advantage of analyzing individual duplicate cores rather than bulking them together is shown by comparing the standard deviations (SD) of the means for the duplicates with the SD of the treatment means (Figure 7). In all treatments the SD for the treatment means were substantially reduced below the highest SD among the plot duplicate means. For example,1150±1532 ppb of imidacloprid was recovered in plot 9 of treatment 4H, Day 1 (Figure 7). The overall treatment mean and SD was 743±491 ppb. If the six cores from the three plot replicates had been handled as six independent replicates rather than as three sets of duplicates, then the imidacloprid concentration would have been 743±833 ppb.

The observed variability in residues among different soil profiles of the same treatment was unlikely to have arisen from laboratory subsampling errors or cross contamination of successive profile soil layers. As previously discussed under 'Analytical Methods', the CV for subsampling averaged 25%, and care was taken in the field to eliminate cross contamination. Thus, the variation between profiles of similar treatments more likely resulted from differences in flow path of emitted water along the length of irrigation pipe and the difficulty in precisely sampling this flow path for solutes. Field sampling variability may be difficult to overcome, but its negative effects on quantitative comparisons between management practices can be alleviated by analyzing individual cores from an experimental replicate rather than bulking them together before analysis.

Conclusions

Because of the need for soil and water conservation in irrigated regions, growers have been gradually adopting drip irrigation systems. Pesticide behavior must be studied in these systems to learn how irrigation scheduling can be manipulated to control agrochemical movement. As a candidate systemic insecticide for chemigation through drip irrigation systems, imidacloprid makes a good model for studying the effects of water management. We showed that imidacloprid can move a radial distance of at least 30 cm from a drip emitter, but the distribution is not homogeneous. Over the course of a growing season, imidacloprid can leach to a depth of at least 150 cm, especially if irrigation is scheduled without attention to the optimal soil matric potential. However, if

irrigation scheduling is triggered by a predefined soil matric potential that is matched to crop needs, imidacloprid leaching can be significantly retarded. Field studies that attempt to quantitatively compare different management practices can benefit from individual analyses of duplicate plot samples rather than analyses of composite samples.

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