Herbicide Losses in Runoff of Containerized Plant Production Nurseries

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SUMMARY. Herbicide use in containerized plant production nurseries is a vital tool for weed management and the production of plants desired by the consumer. Clemson University researchers have conducted studies aimed at determining the amount of herbicide runoff during normal nursery operation, if herbicides accumulate in containment ponds at nurseries, and how herbicide runoff could be reduced. A 2-year study at commercial nurseries found that herbicide concentrations were higher in containment ponds soon after herbicide application, when compared with months with less herbicide application; and herbicides did not accumulate over the 2-year period. Herbicide runoff was greatest immediately after application and up to 15% of the herbicide applied was lost in the first irrigation event after application when using more water soluble herbicides. Bed material and herbicide formulation were also important in determining the amount of herbicide lost. Total losses were highest from plastic- and fabric-covered beds when using granular formulations and highest from gravel beds when spray formulations were used. The combination of using cyclic irrigation and grass waterways resulted in a reduction of about 25% of isoxaben loss when compared with clay and gravel waterways with continuous irrigation. The effects of reduced herbicide treatments compared to standard spray schedules were evaluated on herbicide transport, weed development, and plant growth and health. Results indicated that plant marketability was not affected, and total herbicide runoff was significantly reduced. Based on these studies, several recommendations can be made to commercial container plant production nurseries, which should reduce herbicide runoff and thereby reduce the environmental concerns associated with nurseries.

Herbicide use in containerized plant production nurseries is a vital tool for management of weeds and the production of plants that are desired by the consumer. Weeds may compete for nutrients with the plant being produced and may reduce the marketability of the plant. Herbicides often are used multiple times during the year to control weeds in the container. For example, in South Carolina most nurseries will apply herbicides at least three times during a growing season. These herbicides consist of many different materials with many different formulations and chemistries.

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Fig. 1. Oxyfluorfen applied and levels detected in pond water collected during 1992 at a commercial container plant production nursery (Riley et al., 1994); 1 µg·mL⁻¹ = 1 ppm, 1 kg = 2.2 lb.

Container plant production nurseries have different bed surfaces and production protocols which may affect herbicide usage and possible runoff. One thing that is relatively consistent, however, is that plants generally are watered every day due to the use of potting media that does not retain moisture readily. About 10 years ago, researchers at Clemson University began to investigate questions related to herbicide use and their effects on the surrounding environment, and how the effects of herbicide usage on the environment could be reduced. Our studies began by looking at the overall herbicide usage by nurseries, how these herbicides were applied, and the irrigation methods associated with application. A majority of South Carolina nurseries were applying granular formulations of herbicides two to three times per growing season. Application was followed immediately by overhead irrigation. Previous research had shown that up to 80% of a granular formulation applied to container nurseries may end up on the bed surface and not within the pot, with the percentage lost being determined by the plant shape, spacing and pot size (Gilliam et al., 1992). This information led to several questions, including the following.

What was the possibility of herbicide runoff in commercial container plant production nurseries?

Do herbicides accumulate in ponds used to collect runoff water at nurseries?

If herbicide runoff does occur, are there ways that it could be reduced?

Two commercial nurseries in South Carolina that contained all of their runoff in on-site ponds were used to help answer these questions. The water associated with these ponds was also used as a source of irrigation water.

Herbicide accumulation in ponds

A 2-year study at each of two commercial nurseries was conducted to in-

vestigate the possibility of herbicide accumulation in containment ponds, which could be important when water is then reused for irrigation. Herbicides were applied to nursery beds every 3 months from February to August (three applications per year). Application was followed by overhead irrigation. Water and sediment samples were collected from several sites at each of the containment ponds associated with both nurseries every month. Different herbicides were used at the two nurseries, but overall results were comparable (Camper et al., 1994; Riley et al., 1994).

Herbicides were present in both water and sediment and levels were higher in months following herbicide application. However, herbicide levels did not increase significantly over a 2-year period. Figures 1 and 2 illustrate the levels of oxyfluorfen and pendimethalin that were observed in pond water in the second year at one of the study sites. By the end of the year (December and January) herbicide levels had decreased from the higher levels observed immediately after application early in the spring when levels reached 0.037 µg·mL⁻¹ (ppm) for oxyfluorfen and 0.008 µg·mL⁻¹ for pendimethalin. Oxyfluorfen has a low solubility in water compared to pendimethalin [0.1 and 0.3 µg·mL⁻¹, respectively (Ahrens, 1994)], but there was less pendimethalin detected in water, probably due to the fact that twice as much oxyfluorfen as pendimethalin was applied. Higher herbicide levels were probably observed in

Fig. 2. Pendimethalin applied and levels detected in pond water collected during 1992 at a commercial container plant production nursery (Riley et al., 1994); 1 µg·mL⁻¹ = 1 ppm, 1 kg = 2.2 lb.

Fig. 3. Cumulative oxyfluorfen (OX) and pendimethalin (PD) loss in runoff water from fabric (FR), plastic (PL), and gravel (GV) bedcovers in microplot study (Keese et al., 1994); $28.35 \times 10^6 \mu\text{g} = 1.0 \text{ oz}$.

the spring as a result of decreased herbicide degradation due to lower overall temperatures.

Herbicide runoff occurred from container plants and bed surfaces because herbicides were found in pond water and sediment samples. Studies were then begun to determine what happened immediately following herbicide application and if the type of bed surface would affect herbicide runoff.

Herbicide runoff immediately following application

Herbicide levels in the runoff immediately following application were measured from nursery beds where all runoff water moved in one direction and could be channeled through one sample collection site. Herbicides were applied at standard recommended rates [oryzalin at $1.1 \text{ kg} \cdot \text{ha}^{-1}$ (0.98 lb/acre) a.i., oxyfluorfen at $2.2 \text{ kg} \cdot \text{ha}^{-1}$ (1.96 lb/acre) a.i.] and irrigation water was applied [13 mm (0.5 inch) over 2.5 h]. Water samples were taken from the initiation of runoff (15 min), 30 min, and at 30 min intervals until runoff ceased (3.5 h).

Higher oryzalin than oxyfluorfen levels were observed through 1.5 h, but thereafter oryzalin and oxyfluorfen levels in water were not significantly different (Data not shown) (Keese et al., 1994). Oxyfluorfen levels were relatively consistent throughout the irrigation-runoff event. Cumulative losses of

oryzalin were about four times oxyfluorfen losses (Keese et al., 1994). This difference is probably due to the difference in water solubility of oryzalin and oxyfluorfen [2.6 and $0.1 \mu\text{g} \cdot \text{mL}^{-1}$, respectively (Ahrens, 1994)]. Cumulative losses observed for the two herbicides approximately correspond to the differences in their water solubility. Cumulative losses of oryzalin were significantly higher than oxyfluorfen losses at all sampling times in the runoff event. Total herbicide losses for oryzalin and oxyfluorfen were 4.7% and 0.44%, respectively, indicating a significant difference in the total herbicide losses for the two compounds (Keese et al., 1994).

Comparison of herbicide runoff from different nursery bed materials

Small microplots were used to compare production bed materials commonly used in nurseries. Microplots were set up at the South Carolina Botanical Garden on Clemson University campus and consisted of metal trays [$1 \times 1 \text{ m}$ (39.4 inches)] with height of 15 cm (5.9 inches)] placed on a 5% slope. Trays were filled with 5 cm (2.0 inches) of washed sand and 10 cm (3.9 inches) of coarse gravel. To simulate nursery bed materials the filled trays were covered with a woven polypropylene fabric, a polypropylene plastic sheeting, or left uncovered for the gravel treatment. Azaleas (*Rhododendron obtusum*) in 3-L (0.8-gal) containers with a spacing of 25 cm (9.8 inches) were placed on the bed surfaces. Two herbicide materials, pendimethalin and oxyfluorfen, were applied as a granular formulation at recommended rates to the bed materials which was followed by overhead irrigation [13 mm (0.5 inch)]. Irrigation was applied (13 mm) every day and all water was collected, sampled, and analyzed to determine total herbicide loss over a period of 19 d.

The three nursery bed materials had significantly different herbicide levels in runoff (Fig. 3) with the highest level of oxyfluorfen runoff from plastic bed material and lowest levels from gravel bed material (Keese et al., 1994). Pendimethalin runoff from the bed materials was slightly different with highest losses observed with fabric and plas-

Fig. 4. Cumulative isoxaben in runoff water from granular (GR) and sprayable (SY) formulations applied to plastic (PL), fabric (FR), and gravel (GV) bed surfaces (Wilson et al., 1995); $28,350 \text{ mg} = 1.0 \text{ oz}$.

Fig. 5. Cumulative isoxaben losses during three runoff events (Event 1 = day of application, Event 2 = 2 d after treatment, Event 3 = 5 d after treatment) at a commercial nursery (Wilson et al., 1996); 28.4 g = 1.0 oz.

tic bed materials (Fig. 3) and lowest levels from the gravel bed material. Less herbicide was lost from the gravel beds when using granular material possibly due to the granular formulation being retained in the gravel. Higher herbicide levels of the less water soluble oxyfluorfen were observed on the plastic material possibly due to the physical movement of the granular particles containing the oxyfluorfen instead of the herbicide being soluble in the water runoff. Oxyfluorfen levels were higher overall compared to pendimethalin levels, and this is explained by the commercial herbicide used in this experiment containing twice as much oxyfluorfen as pendimethalin.

Comparison of herbicide runoff from different herbicide formulations

These results had raised new questions. What would be the effect of the herbicide formulation on herbicide runoff? Would sprayable and granular herbicide formulations have the same potential for runoff? Sprayable and granular formulations of isoxaben were compared using the microplots previously described.

The plastic nursery bed surface had 1.5 times isoxaben lost from the granular formulation as compared to the sprayable formulation (Fig. 4) (Wilson et al., 1995). Similar results were observed on the woven fabric nursery bed surface with more herbicide lost when a granular formulation was used (Fig. 4). Losses were different from the gravel production surface. Higher losses were observed from the sprayable formula-

tion on the gravel surface when compared to the granular formulation (Fig. 4). Total losses were highest from the plastic and fabric beds when using granular formulations, and highest from gravel beds when using sprayable formulations.

Results from the comparison of different formulations on different nursery bed materials indicate that a sheeting effect of herbicide loss can occur when granular particles are moved by the water flow, and that losses are not strictly based on water solubility of herbicides. Granular formulations seem to be especially affected by this phenomenon; therefore, the herbicide formulation used should be carefully considered when the nursery bed material has a slick surface (Wilson et al., 1995).

Fig. 6. Cumulative trifluralin losses during three runoff events (Event 1 = day of application, Event 2 = 2 d after treatment, Event 3 = 5 d after treatment) at a commercial nursery (Wilson et al., 1996); 28.4 g = 1.0 oz.

Herbicide runoff over subsequent irrigation events

The next question dealt with whether the same type of results would be obtained in a commercial nursery using standard management practices. How long would herbicide runoff occur following herbicide application?

Granular herbicide formulations are preferred by the nursery industry because of their effectiveness and ease of application. A granular herbicide containing isoxaben and trifluralin was applied at 0.68 and 2.72 kg·ha⁻¹ (0.607 and 2.427 lb/acre) to a 2-ha (4.9-acre) containerized plant production area that was sloped so all runoff water drained into a 0.5-ha (1.2-acre) containment pond through a single storm drain. Bed surfaces were covered with a combination of woven landscape fabric and polypropylene plastic, and surrounded by clay and gravel drainage ways. Overhead sprinkler irrigation was applied following herbicide application and runoff water samples were collected prior to entering the collection pond. Samples were collected on the day of treatment (DOT) and 2 and 5 d after treatment (DAT). Cumulative loss of both herbicides was greatest during the runoff event immediately following application (Figs. 5 and 6) (Wilson et al., 1996). About 6% of applied isoxaben was moved from the application site during the first irrigation event. Losses from the second and third irrigation events were 2% and 1%, respectively, for a total of 9% loss within 5 DAT (Fig. 5).

Table 1. Total isoxaben in runoff water (± 1 SD) and percentage of total applied in water coming from grass and clay and gravel waterway treatments (Briggs et al., 1998b).

Collection date	Clay and gravel waterway treatment		Grass waterway treatment		LSD ^z P = 0.05
	Isoxaben (g) ^y	Proportion of total applied (%)	Isoxaben (g)	Proportion of total applied (%)	
DOA ^x	68 $\pm$ 19.8	13	57 $\pm$ 25.4	11	9.0
1 DAA ^w	27 $\pm$ 2.6	5	32 $\pm$ 7.5	6	10.0
2 DAA	21 $\pm$ 1.4	4	25 $\pm$ 3.8	5	5.8
4 DAA	4 $\pm$ 1.0	0.7	7 $\pm$ 5.8	1	6.3
8 DAA	ND ^v	---	0.7 $\pm$ 0.7	0.002	---
Total	121 $\pm$ 14.5	23%	122 $\pm$ 40.7	23%	28.6

^zLSD = least significant difference for grams of isoxaben for specific day or total between treatments.

^y28.4 g = 1 oz.

^xDOA = day of application.

^wDAA = days after application.

^vND = none detected.

These results were similar to results obtained previously at the same site with oryzalin (Keese et al., 1994). Similar water solubilities of isoxaben and oryzalin [1 and 2.6 $\mu\text{g}\cdot\text{mL}^{-1}$, respectively (Ahrens, 1994)] probably account for the similar losses. Cumulative trifluralin losses were 1% during the first runoff event, followed by 0.1% and 0.02% for the second and third runoff events, respectively, for a total of 1.1% total loss through 5 DAT. The lower losses observed with trifluralin are attributed to its lower water solubility [0.3 $\mu\text{g}\cdot\text{mL}^{-1}$ (Ahrens, 1994)] since total amounts applied were about four times that of isoxaben. This research suggests water solubility is an important factor to consider when determining possible herbicide runoff.

Options to reduce herbicide runoff in commercial nurseries

Since all of our studies indicate that herbicides are detected in runoff water, especially with more water soluble materials, What we can do to reduce herbicide runoff? Several possibilities have been suggested such as alterations in

formulation type, alterations in irrigation practices (pulse versus continuous irrigation and delaying the onset of irrigation following herbicide application), addition of vegetative waterways, and the adjustment of weed management practices.

Vegetative filter strips or grass waterways have previously been shown to reduce atrazine losses from agricultural fields by 55% when runoff water was directed through grass filter strips (Mickelson and Baker, 1993). To test this possibility in a commercial container plant nursery, a hybrid bermudagrass (*Cynodon dactylon* $\times$ *C. transvaalensis*) waterway [1.8 $\times$ 89.6 m (2 $\times$ 98 yards)] was installed downslope of four adjacent growing beds [about 1 ha (2.5 acres)] and compared to a clay and gravel waterway with four adjacent growing beds. Weirs were placed at the end of both waterways to allow determination of runoff volumes and for sample collection. Granular isoxaben and trifluralin were applied at rates a.i. of 1 and 4 $\text{kg}\cdot\text{ha}^{-1}$ (0.9 and 3.6 lb/acre), respectively, and followed by irrigation.

Results of the effect of the grass waterway are shown in Table 1 (Briggs

et al., 1998a). The presence of the grass waterway delayed isoxaben runoff, but the overall loss over an 8-d period following application was not significantly different from herbicide losses through a clay and gravel waterway. The delay observed in runoff, however, could be extremely important when working with herbicides that rapidly degrade by photolysis or readily volatilize.

Grass waterways would probably be more effective if irrigation levels were reduced or adjusted to reduce the total amount of runoff. One way of possibly reducing the total runoff is to use cyclic or pulse irrigation which is defined as a sequence of timed cycles composed of an irrigation phase and a resting phase (Karmeli and Peri, 1974). Studies were set up on the site previously described. The clay and gravel waterway treatment had continuous irrigation [1.5 h, 1.9 cm (0.75 inch) total] beginning immediately after herbicide application and the grass treatment area was irrigated with three 30-min cycles [0.6 cm (0.24 inch) irrigation/cycle] having a 90 min interval between cycles with the first irrigation cycle beginning immediately after herbicide application. The com-

Table 2. Isoxaben in runoff water on 0, 1, 2, 4, and 8 d after application and total losses in runoff water from continuous irrigation and cyclic irrigation and grass waterway treatments (Briggs et al., 1998a).

	Isoxaben (g) ^z					
	Days after application					
	0	1	2	4	8	Total
Continuous irrigation	18.9	9.6	10.4	4.2	2.1	45.3
Cyclic irrigation and grass waterway	12.5	6.6	6.7	3.3	2.3	31.5
LSD ² (<i>P</i> = 0.05)	5.9	13.7	5.5	2.9	4.5	9.8

^z28.4 g = 1.0 oz.

²LSD = least significant difference between treatments on specific days and for total.

bination of cyclic irrigation and grass waterways resulted in a reduction of about 25% in total isoxaben loss when compared with a clay and gravel waterway with continuous irrigation treatment (Table 2) (Briggs et al., 1998b).

Sprayable and granular formulations of isoxaben and trifluralin at a commercial nursery were compared when using cyclic irrigation. Spray and granular formulations were applied to each of four beds [89.6 × 18.3 m (98 × 20 yards)] which had landscape fabric over a gravel base. Beds were sloped (1% to 2%) toward a base where weirs had been installed at the base to channel runoff water through the weirs allowing sample collection and volume determination. Application rates were 1.1 kg·ha⁻¹ (0.98 lb/acre) isoxaben and 4.4 kg·ha⁻¹ trifluralin (3.93 lb/acre). Irrigation after application was three cycles, 30 min each with a 90-min rest period between cycles. Three runoff samples were collected at 15-min intervals for each irrigation cycle on the day of application (DOA), and on 1 and 2 d after application (DAA).

Total isoxaben and trifluralin recovered are shown in Table 3 (Briggs et al., 2002). Minimal differences for individual days and in total trifluralin in runoff were detected between applications of spray and granular formations, possibly due to its low water solubility which results in low runoff levels. Isoxaben runoff was significantly

higher from the granular formulation when compared to the spray formulation with about a 25% reduction observed with the spray formulation. Reductions of runoff of 25% could be extremely important when compounds are not readily degraded in the environment.

Reduced herbicide treatments effect on weed development and plant marketability

The impact of reduced herbicide treatment compared to standard spray schedules on herbicide transport in runoff water from application site in container nurseries, in addition to subsequent weed development and plant growth and health, was studied. Eight contiguous production beds (89.6 × 18.3 m) were randomly assigned to the two treatments. Beds contained 25 plant species in 11-L (2.9-gal) pots, and the marketability of the plants and the weed presence were assessed at the end of the growing season. For the reduced herbicide treatment one herbicide treatment was applied near the end of the growing season (Sept. 1998). The preventive herbicide treatment had two herbicide applications during the 1998 growing season (July and September). Production areas had a base of landscape fabric overlaid on plastic and were sloped 1% to 2% so that water was channeled into weirs installed at

the lowest point. Weeding was done in both treatments in September and again in November. Weed species number and dry weights were determined for both weeding dates in both treatments.

Total herbicides detected in runoff from the reduced herbicide treatment were 1.3 g (0.046 oz) oxyfluorfen and 0.7 g (0.025 oz) pendimethalin and from the preventive practice treatment were 1.3 g oxyfluorfen, 0.7 g pendimethalin, 11.1 g (0.391 oz) isoxaben, and 1.6 g (0.056 oz) trifluralin (Briggs et al., 2001). The cost of hand weeding associated with the preventative herbicide treatment was based on an average of 69 h·ha⁻¹ (27.9 h/acre) for a total weed management cost of \$1271/ha (\$514/acre) (including herbicides and application costs) while the cost of weeding the reduced herbicide treatment calculated to be 159 h costing \$1590/ha (\$643/acre) resulting in a 25% higher cost. No differences in container plant growth were found when plants were assessed at the end of the season even though there were significant differences in the weed numbers between the treatments. Plant marketability was not affected by the reduced herbicide treatment and the reduced herbicide runoff could offset increased costs associated with hand weeding.

Present studies include evaluating the effect of reducing or delaying irrigation immediately after herbicide

Table 3. Isoxaben and trifluralin amounts recovered (total amount and percent of applied) in runoff water from the spray and granular formulations applied on the day of application (DOA) and 1 and 2 d after application (DAA). Means are of three replications (Briggs et al., 2002).

Chemical	Spray amount recovered		Granular amount recovered		LSD ^z (P=0.05) (g)
	(g) ^y	Proportion of applied (%)	(g)	Proportion of applied (%)	
Isoxaben					
DOA	8.02	4.6	7.92	4.5	2.38
1 DAA	2.63	1.5	4.86	2.8	1.45
3 DAA	2.13	1.2	3.28	1.8	1.16
LSD ^x (P = 0.05)	2.18		0.85		
Total	12.78	7.3	16.06	9.1	1.72
Trifluralin					
DOA	2.24	0.3	1.63	0.2	0.42
1 DAA	0.76	0.1	1.14	0.2	0.25
2 DAA	0.59	0.1	0.83	0.1	0.23
LSD (P = 0.05)	0.30		0.29		
Total	3.29	0.5	3.61	0.5	0.61

^zLSD = least significant difference between treatments on specific day or for total.

^y28.4 g = 1 oz.

^xLSD = least significant difference for specific herbicide between days within treatment.

application. Preliminary results indicate that the reduction in irrigation immediately following herbicide application may reduce herbicide runoff in some cases but not in others. The differences could be the result of chemical properties of the herbicides being studied. Runoff of compounds, which are unstable and rapidly break down following application, may be reduced by minimizing the irrigation volume immediately following application. Reducing the initial irrigation volume did not affect weed control efficacy and reductions in irrigation volume should be further investigated to determine the optimum amount of irrigation volume following application.

Conclusions

Based on the studies completed, several recommendations can be made to reduce herbicide runoff in container plant production nurseries. These recommendations include the following.

Use of the formulation/herbicide most appropriate for the container nursery. Less water soluble herbicides are generally not as prevalent in runoff water and granular formulations may be transported more easily on plastic and fabric surfaces where the granule itself can be moved in the water flow.

Vegetative strips, such as grass, may delay herbicide losses in runoff, but total water runoff should be reduced to allow more time for possible breakdown and/or adsorption.

Irrigation practices should be altered to reduce water runoff volume following a herbicide application. Cyclic irrigation or reduced irrigation have been shown to reduce herbicide runoff. Increases in the time interval between the herbicide application and irrigation can also have significant effects on runoff.

Less aggressive weed control (fewer herbicide applications) should be considered since no effect was noted in the plant species evaluated when herbicide applications were reduced. However, container plant age and size may be important factors in decisions regarding herbicide usage.

Herbicide applications and runoff reduction can be important both to the initial control obtained and length of control provided. However, and possibly more importantly, it can result in reduced environmental concerns associated with nurseries. Some plant species have been previously shown to be affected by low levels of herbicides that may be present in runoff (Bhandary et al., 1997). This is a factor that may be very subtle and hard to detect when it occurs. Our overall goal should be to reduce herbicide runoff whenever possible, and thereby reduce potential harm to the environment as well as the general public's environmental concerns.

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