Spray nozzle selection contributes to improved postemergence herbicide crabgrass control in turfgrass

Edward Nangle,¹ Zane Raudenbush,¹ Tyler Morris,¹ Michael Fidanza²

¹Ohio State University, Agricultural Technical Institute, Wooster, OH; ²Pennsylvania State University, Reading, PA, USA

Correspondence: Michael Fidanza, Pennsylvania State University, Berks Campus, Reading, PA, 19610, USA. E-mail: maf10@psu.edu

Key words: Application, crabgrass; Digitaria; droplet; efficacy; herbicide; lawn; nozzles; postemergence; spray; turf; turfgrass.
Highlights

- In turfgrass sites with low crabgrass pressure, one postemergence application of quinclorac herbicide could potentially achieve acceptable control with spray nozzles that produce spray droplets ranging from ultra coarse (> 650 µm) to fine (145 - 225 µm).

- In turfgrass sites with heavy crabgrass population and pressure, one postemergence application of quinclorac herbicide is best optimized with spray nozzles that produce spray droplets ranging from very coarse (401 - 500 µm) to medium (226 - 325 µm).

- Overall, turfgrass management practitioners should avoid using spray nozzles that produce a hollow cone spray pattern with ultra coarse (> 650 µm) spray droplets which can result in poor or irregular herbicide coverage, or fine (145 - 225 µm) spray droplets which are subject to potential drift and possible negative off-target effects.

- Overall, in an effort to reduce herbicide use for postemergence crabgrass control, a single quinclorac herbicide application could be properly timed and optimized with nozzles that produce spray droplets ranging from very coarse (401 - 500 µm) to medium (226 - 325 µm) in size, however, future research should consider cultural practices that would further optimize and also reduce herbicide applications.

Abstract

For optimum postemergence crabgrass (Digitaria spp.) control, a single quinclorac herbicide application could be properly timed and delivered with spray nozzles that produce spray droplets ranging from very coarse (401 - 500 µm) to medium (226 - 325 µm) in size to maximize target coverage and minimize the potential for drift. Crabgrass is an invasive annual grass weed of cool-season turfgrass maintain as lawns, golf courses, and sports pitches. Postemergence herbicide applications for crabgrass control in turfgrass swards often rely on repeated applications for effective control. Optimizing postemergence crabgrass applications can reduce pesticide inputs and contribute to sustainable turfgrass management practices. Two field studies evaluating crabgrass control were
conducted in 2020 in a mixed stand of Kentucky bluegrass (*Poa pratensis* L.) with perennial ryegrass (*Lolium perenne* L.) in Ohio (USA) and in perennial ryegrass in Pennsylvania (USA). Both sites have histories of natural crabgrass (*Digitaria sanguinalis* (L.) Scop.) infestation. A postemergence herbicide, quinclorac, was applied at the product label rate and tank-mixed with methylated seed oil at the crabgrass plant stage of three leaf to one tiller. Different spray nozzles were selected to deliver the following spray droplet classifications and sizes at 275 kPa: Delavan Raindrop 1/4, ultra coarse (> 650 µm); TurfJet 1/4TTJO4, extremely coarse (501 - 650 µm); Air Induction AA8004 or XRTeeJet 8015, very coarse (401 - 500 µm); XR TeeJet 8008 or GreenLeaf TDAD04, coarse (326 - 400 µm); XR TeeJet 8004, medium (226 - 325 µm); and XRTeeJet 8003 fine (145 - 225 µm). Crabgrass pressure was low in Ohio, and herbicide efficacy at 60 days after treatment was considered acceptable when applied from all spray nozzles that produced spray droplet sizes ranging from ultra coarse to fine. Crabgrass pressure was severe in Pennsylvania, and herbicide efficacy at 60 DAT was considered marginally acceptable when applied from spray nozzles that produced spray droplet sizes ranging from very coarse to medium. Future research should consider cultural practices that would be complimentary to postemergence herbicide applications with the goal to further reduce pesticide use and minimize any potential environmental impacts related to spray drift.

**Introduction**

Crabgrass (*Digitaria* spp.) is considered the most invasive and troublesome weed of cool-season lawns and managed recreational turfgrass swards (Dernoeden et al., 2003; Watschke et al., 2013). Crabgrass is a warm-season annual grass species that first germinates and emerges in the spring, but emergence can continue into the summer (Fidanza et al., 1996). In mid-summer, crabgrass becomes more competitive and can aggressively spread throughout a cool-season turfgrass stand. Turfgrass professionals apply preemergence herbicides as a commonly used strategy to provide season-long suppression of crabgrass (Watschke et al., 2013). An inaccurately timed application, incorrect application rate, unseasonably wet weather, or extended crabgrass germination and emergence
periods may reduce the efficacy of preemergence herbicides (Brosnan et al., 2014; Martin and Sullivan, 1996; Fidanza et al., 1996). When poor crabgrass control is observed from a preemergence herbicide application, a postemergence herbicide application is warranted (McCarty et al., 2005). In the USA, quinclorac (3,7-dichloro-8-quinolinecarboxylic acid) herbicide is used for postemergence crabgrass management in turf maintained as lawns, golf course, and sports pitches (Chism and Bingham, 1991; Johnson, 1994; McCarty et al., 2005). Quinclorac is classified as a group 4 herbicide and is a quinolone carboxylic acid which acts as an auxin mimic at the site of the cell wall synthesis in roots and inhibits the development of cellulose by 70% and other cell wall components by 50 to 60% (Grossman, 1998; Koo et al., 1997; Senseman, 2007). Quinclorac acts quickly with peak concentration measured in roots after 6 H and foliage after 8 H (Koo et al., 1997; Berghaus and Wuerzer, 1989). Quinclorac uptake is accelerated by various climactic conditions such as high light intensity or sufficiently moist soil (Grossman, 1998). Susceptible plants treated with quinclorac experience rapid inhibition of shoot growth, and development of chlorotic juvenile tissue followed by necrosis of the shoots (Grossmann and Kwiatkowski, 1993; Koo et al., 1991; Koo et al., 1997). In practice, quinclorac in the form of a commercially formulated herbicide is tank-mixed with methylated seed oil to improve efficacy (McCarty et al., 2005). The addition of spray adjuvants such as surfactants and oils results in greater uptake of quinclorac due to enhanced penetration into the leaf as well as maintaining the quinclorac in solution rather than crystalizing on the leaf surface (Steinke and Stier, 2002; Woznica et al., 2003). Recent advances with pesticide application technology includes spray nozzles (i.e., spray tips) that improve delivery of foliar applied herbicides (Contiero et al., 2016; Creech et al., 2015), and also utilize correct spray nozzles and techniques to reduce spray drift to non-target sites (Grella et al., 2020; Kalsing et al., 2018). The spray nozzle produces a spray pattern which contains spray droplets in various sizes depending on the nozzle type (ASABE, 2009; Lake, 1977). A larger spray droplet size translates to poorer coverage (i.e., less droplets per unit area) but better at drift reduction as compared to smaller spray droplets that facilitates better coverage (i.e., more droplets per unit area).
but are more prone to drift off target (ASABE, 2009; Creech et al., 2015; Fidanza et al., 2009a; Fidanza et al., 2009b; Kaminski and Fidanza, 2009; Stainier et al., 2006).

The spray droplet sizes are based on the manufacturer’s laboratory analysis and specifications (ASABE, 2009; Creech et al., 2015). Since all spray nozzles produce a range of droplet sizes within their spray pattern, the volume mean diameter (VMD) value represents 50% of the total volume of liquid spray comprised of droplets within diameters larger than the median value, and 50% smaller than the median value (ASABE, 2009). Droplet size information is provided by the manufacturer for various nozzle types at various application pressures (ASABE, 2009).

If quinclorac efficacy of a single postemergence crabgrass application could be improved using a specific spray nozzle, this could negate the need for repeated postemergence applications (Dernoeden et al., 2003; Fidanza et al., 1996; McCarty et al., 2005; Watschke et al., 2013). This would also help reduce any potential for environmental contamination, to aid turfgrass managers in reducing herbicide applications and overall weed control costs, and potentially reduce overall pesticide usage. The effect of the spray nozzle has not been evaluated for the use of quinclorac on postemergence control of crabgrass. Therefore, the objective of this field study was to evaluate the efficacy of various spray nozzles which produce various spray droplet sizes on a single quinclorac herbicide application for postemergence control of crabgrass in cool-season turfgrass.

Materials and methods

A field study was conducted at two locations, in Hinckley, Ohio (USA), and Reading, Pennsylvania (USA). At both sites, one postemergence herbicide treatment was applied when most of the crabgrass plants were at the one tiller plant growth stage. At both locations, quinclorac (Drive XLR8®, water-based formulation; 180 g ai•L⁻¹; BASF, Research Triangle Park, NC, USA) was applied at the product label rate of 9.16 kg a.i•ha⁻¹ tank-mixed with 1.75 L methylated seed oil•ha⁻¹. Treatments consisted of the herbicide delivered through eight different spray nozzles, which produced different spray droplet sizes classified from fine to ultra coarse (Table 1).
Ohio

The site was located on a mixed stand of unknown cultivars of Kentucky bluegrass (*Poa pratensis* L.) and perennial ryegrass (*Lolium perenne* L.) maintained as a golf course fairway (Hinckley Hills Golf Course; Hinckley, Ohio, USA). The turf was maintained at a height of 25 mm and typically mowed three times per week during the growing season with a reel mower and clippings were not removed. The native clay soil rootzone had a pH of 6.4 with 4.4% organic matter. The site has a history of crabgrass infestation. No fertilizer or pesticides (i.e., insecticides or fungicides) were applied prior to or during the study period.

Plot sizes were 0.9 × 1.5 m and organized in a randomized complete block design with four replications. All treatments were applied from a CO$_2$-powered backpack sprayer (Bellsprayers Inc., Opelousas, LA, USA) at 275 kPa, from a single handheld nozzle boom through a water-carrier volume of 407 L•ha$^{-1}$ to evenly cover the entire plot at 4.8 km•H$^{-1}$ groundspeed. The sprayer was calibrated for each nozzle to deliver 407 L water•ha$^{-1}$ prior to initiation of the study.

Treatments were applied on 24th June 2020 when average crabgrass was visually determined to be at the three to four leaf stage. Average plot area covered with crabgrass prior to treatment applications was 24% based on visual assessment. The soil temperature at a 38 mm depth was measured at 1100 H and averaged 18.1$^\circ$C with an average soil moisture of 23.8% (Field Scout 300 TDR Soil Moisture Meter; Spectrum Technologies, Aurora, IL, USA) across the study site. On 1st July 2020, a granular application of prodiamine (Barricade® formulated as a granular product with 0.48% active ingredient; The Andersons Inc., Maumee OH, USA) was applied to the entire study site at the product label rate of 1110 g a.i•ha$^{-1}$ followed by irrigation to a depth of 7 mm to prevent further crabgrass germination and emergence.

Pennsylvania

The study site was located on a mature perennial ryegrass (*Lolium perenne* L., ‘Double Eagle’ blend)
stand, maintained as a residential lawn, with a history of natural crabgrass emergence, at the Center for the Agricultural Science and a Sustainable Environment (Pennsylvania State University, Berks Campus, Reading, PA, USA). The rootzone was a loam soil with pH = 6.1 and 3.6% organic matter. The site received 49 kg N•ha⁻¹ from granular urea (46N-0P₂O₅-0K₂O) on 5th May 2020, with no other fertilizer or pesticide inputs prior to or during the study period. Turf was mowed with a rotary mower once or twice per week at a height of 64 mm, and clippings not removed.

Individual plot size was 1 × 1.5 m, and treatments were arranged as a randomized complete block design with four replications. All treatments were applied from a CO₂-powered backpack sprayer (Bellsprayers Inc., Opelousas, LA, USA) at 275 kPa, from a hand-held single nozzle boom, and in a water-carrier volume of 407 L•ha⁻¹ to evenly cover the entire plot at 4.8 km•H⁻¹ groundspeed. Prior to the start of the study, the sprayer was calibrated for each nozzle to deliver 407 L water•ha⁻¹.

All treatments were applied on 25th June 2020. Average crabgrass growth stage was visually determined to be four leaf to one tiller stage, and the average crabgrass population was 37% plot area covered. At approximately 1000 H on 25th June 2020, average soil temperature across the study area at the 38 cm depth was 21.0 °C, and average volumetric water content was 23.2% (Field Scout 300 TDR Soil Moisture Meter; Spectrum Technologies, Aurora, IL, USA). The study site was mowed on 22nd July 2020, which was three days prior to treatment applications.

In order to suppress potential crabgrass seedlings from germinating and emerging after quinclorac treatments were applied, the entire study site received an application of pendimethalin (Pendulum AquaCap® formulated as 455 g ai•L⁻¹; BASF, Research Triangle Park, NC, USA) preemergence herbicide on 28th June 2020. Pendimethalin herbicide was applied to the entire study site at the product label rate of 645 g a.i•ha⁻¹. The entire site was irrigated with approximately 7 mm water immediately following application to rinse-in the herbicide into the upper rootzone.

**Data collection and data analysis**

Plots were visually evaluated for percent plot area covered with crabgrass approximately every seven
to ten days from 24th June to 23rd August 2020 in Ohio, and from 25th June to 24th August 2020 in Pennsylvania. The end of the study in Ohio and in Pennsylvania represented 60 DAT (days after treatment), and therefore only initial (0 DAT) and end 60 (DAT) data are presented. Plot area covered with crabgrass at $\leq 10\%$ is considered acceptable, 11 to 25% is marginally acceptable, and $\geq 26\%$ is not acceptable (Dernoeden et al., 2003; Watschke et al., 2013). At both locations, percent control per plot was determined by comparing initial crabgrass plot area covered at the start of the study to final crabgrass plot area covered at the end of the study, using the following formula:

$$\text{Percent plot area cover in untreated plot} - \frac{\text{Percent plot area cover in treated plot}}{\text{Percent plot area cover in untreated plot}} \times 100.$$ 

Crabgrass control at $\geq 90\%$ is considered acceptable, 75 to 89% is marginally acceptable, and $\leq 74\%$ is not acceptable (Dernoeden et al., 2003; Watschke et al., 2013). All data were analyzed using Agricultural Research Manager (GDM Solutions, Brookings, South Dakota, USA), and treatment means were compared using Fisher’s protected least significance difference test at $P \leq 0.05$ (Mead et al., 2003).

**Results**

Examination of analysis of variance of data revealed a non-significant replication effect at Ohio ($P < 0.0801$) and Pennsylvania ($P < 0.1906$) at the start of the study, thus indicating a uniform crabgrass population among all four replications at both locations (Table 2). At 60 days after treatment (DAT), analysis of variance for replication effect was not significant (ranging from $P < 0.0841$ to $P < 0.9327$) at both locations, but treatment effect was significant ($P < 0.001$) at both locations (Table 2).

**Ohio**

At the start of the study on 24th June 2020, average plot area covered with crabgrass in the untreated
plots was 28% and progressed to 41% by 24th August 2020 (60 DAT) (Table 3). This amount of crabgrass emergence was considered to be of low (< 50% plot area covered) pressure.

At 60 DAT, all plots treated with herbicide had crabgrass coverage ranging from < 1 to 7% plot area covered, which was significantly lower than crabgrass observed in the untreated plots of 41% (Table 3). With all herbicide-treated plots, no significant differences were observed among all herbicide-spray nozzle treatments (Table 3).

At 60 DAT, best crabgrass control (95 to 98%) was observed in plots treated from nozzles that produced ultra coarse, very coarse, coarse, medium, or fine spray droplets, but lowest control (83%) observed in plots treated from nozzles that produced from extremely coarse spray droplets (Table 3). No significant differences were detected, however, in plots treated from nozzles that produced ultra coarse, extremely coarse, or coarse (dual flat fan nozzle only) spray droplets (Table 3). No turfgrass injury or phytotoxicity was observed at any time from the herbicide application.

**Pennsylvania**

At the initiation of the study on 25th June 2020, average plot area covered with crabgrass in the untreated plots was 40%, which progressed to 84% by 24th August 2020 (60 DAT), thus illustrating the aggressive and invasive nature of the heavy (> 50% plot area covered) crabgrass population at this study site (Table 3). At 60 DAT, all plots treated with herbicide had 12 to 35% plot area covered with crabgrass, which was significantly less than crabgrass observed in the untreated plots with 84% (Table 3).

At 60 DAT, lowest crabgrass coverage was observed in plots treated from nozzles that produced very coarse spray droplets at 12 to 17% (Table 3). Plots treated from nozzles that produced extremely coarse, coarse, or medium spray droplets resulted in 20 to 24% plot area covered with crabgrass (Table 3). No significant differences, however, were detected when comparing data from plots treated from nozzles that produced extremely coarse, coarse, or medium spray droplets (Table 3).

Best crabgrass control at 60 DAT was observed in plots treated from nozzles that produce very coarse
spray droplets at 80 to 86%, followed by extremely coarse, coarse, or medium spray droplets at 71 to 76% (Table 3). Poorest control was observed in plots treated from nozzles that produce ultra coarse or fine spray droplets at 58 to 63% (Table 3). As observed in the field site located in Ohio, no turfgrass injury or phytotoxicity was observed from the herbicide application at any time during in the Pennsylvania study.

**Discussion**

It is conceivable for turfgrass sites in Ohio with low crabgrass population of < 50% plot area covered, one single postemergence quinclorac herbicide application could potentially achieve acceptable control (≥ 90% control) as delivered from a spray nozzle that produces spray droplet sizes ranging from ultra coarse (Delavan Raindrop 1/4) to fine (XR TeeJet 8003). Under heavy crabgrass pressure of > 50% plot area covered in Pennsylvania, achieving ≥ 90% control of crabgrass would be most desired and acceptable, however, 75 to 89% control would be considered marginally acceptable to the turfgrass practitioner (Watschke et al., 2013). At the Pennsylvania site, no significant differences were detected when comparing percent crabgrass control in plots treated from nozzles that produced extremely coarse (TurfJet 1/4TTJO4), very coarse (Air Induction AA8004, XR TeeJet 8015), coarse (XR TeeJet 8008, GreenLeaf TDAD04), or medium (XR TeeJet 8004) spray droplets, and all produced a marginally acceptable 71 to 86% crabgrass control. Also at the Pennsylvania site, unacceptable 58 to 63% crabgrass control was observed in plots treated from nozzles that produced ultra coarse (Delavan Raindrop 1/4) to fine (XR TeeJet 8003) spray droplets.

Therefore, in turfgrass sites with heavy crabgrass population and emergence pressure (≥ 50% plot area covered), one single postemergence quinclorac herbicide application could be maximized by using a spray nozzle that produce a very coarse (Air Induction AA8004, XR TeeJet 8015), coarse (XR TeeJet 8008, GreenLeaf TDAD04), or medium (XR TeeJet 8004) spray droplet size in a flat fan spray pattern. Spray nozzles that produce ultra coarse (Delavan Raindrop 1/4) and extremely coarse (TurfJet 1/4TTJO4) spray droplets have a much larger or “raindrop” droplet size that is less prone to
drift, but coverage on a turfgrass stand is poor, especially from a hollow cone spray pattern (Fidanza et al., 2009a, Fidanza et al., 2009b). A nozzle that products fine spray (XR TeeJet 8003) droplets conceivably provide better surface coverage but those smaller droplets are easily prone to drift and thus could cause the herbicide to move into non-target areas.

The ability to achieve acceptable postemergence crabgrass control from quinclorac delivered at a water carrier volume of 407 L•ha⁻¹ also is worth noting. In the USA, turfgrass industry practitioners typically apply herbicides, fungicides, and other plant and soil health products at one gallon water carrier•1000 ft⁻², which equates to 407 L water carrier•ha⁻¹ (Fidanza et al., 2009a; Watschke et al., 2013). This amount of water carrier affords the turfgrass manager the ability to essentially cover more surface area with application equipment due to less downtime on otherwise multiple spray tank refills with higher water carrier volumes (McCarty et al., 2005). This represents a time and financial savings and could be an incentive for turfgrass managers to improve the performance of their pesticide and product spray equipment through water carrier volume and spray nozzle selection.

Conclusions

These are the first studies to evaluate the potential effects of spray nozzles to optimize postemergence crabgrass control in turfgrass from quinclorac herbicide. In the Ohio study, crabgrass was treated with a postemergence application of quinclorac when crabgrass was at the three to four leaf growth stage, and at the four leaf to one tiller growth stage in the Pennsylvania study. Quinclorac is more efficacious when applied to younger crabgrass smaller than the two tiller growth stage, or applied to mature crabgrass larger than the four tiller growth stage. Therefore, turfgrass managers must be vigilant about timing a postemergence quinclorac application during those favorable crabgrass growth stages.

Overall, results from these Ohio and Pennsylvania studies support the practice of applying a properly timed single postemergence quinclorac application using a spray nozzle that produces an extremely coarse, very coarse, or medium spray droplet size in a flat fan spray pattern. There was some variation...
with crabgrass population and pressure between the two study sites, and therefore further collaborative research efforts are needed to aid with developing sustainable weed control recommendations for precision turfgrass management. The selection of proper spray nozzle type that delivers the optimum spray droplet spectra is an important strategy to improve the efficiency of postemergence crabgrass herbicide applications and at the same time minimizing any potential environmental impacts related to spray drift.

References

ASABE, 2009. Spray nozzle classification by droplet spectra. St. Joseph, MI. https://doi.org/ANSI/ASAE S572.1 (ASABE = American Society of Agricultural and Biological Engineers).

Berghaus R, Wuerzer B, 1989. Uptake, translocation and metabolism of quinclorac (BAS 514H) in rice and barnyard grass. pp 133-139 in Proc. of 12th Asian-Pacific Weed Science Society Conference, Taipei, Taiwan.

Brosnan JT., Breeden GK, Vargas JJ, 2014. Influence of simulated rainfall on large crabgrass control with two quinclorac-containing herbicides. Applied Turfgrass Science https://doi.org/10.2134/ATS-2013-0004-BR.

Chism WJ, Bingham SW, 1991. Postmergence control of large crabgrass (Digitaria sanguinalis) with herbicides. Weed Science 39:62-66.

Contiero RL, Biffe DF, Constantin J, De Oliveria Júnior RS, Braz GBP, Lucio FR, Schleier JJ. 2016. Effects of nozzle types and 2,4-D formulations on spray deposition. Journal of Environmental Science and Health 51:888-893.

Creech CF, Henry RS, Fritz, BK, Kruger GR, 2015. Influence of herbicide active ingredient, nozzle type, orifice size, spray pressure, and carrier volume rate on spray droplet size characteristics. Weed Technology 29:298-310.

Dernoeden PH, Bigelow CA, Kaminski JE, Krouse JM, 2003. Smooth crabgrass control in perennial
ryegrass and creeping bentgrass tolerance to quinclorac. HortScience 38(4):607-612.

Fidanza MA, Dernoeden PH, Zhang M, 1996. Degree-days for predicting smooth crabgrass emergence in cool-season turf. Crop Science 36:990-996.

Fidanza MA, Kaminski JE, Agnew ML, Shepard D, 2009a. Evaluation of water droplet size and water-carrier volume on fungicide performance for anthracnose control on annual bluegrass. International Turfgrass Society Research Journal 11:195-205.

Fidanza MA, Gregos JS, Aynardi B, Hudson D, 2009b. Evaluation of fungicides and water-carrier droplet size for dollar spot control in creeping bentgrass, 2006. Plant Disease Management Reports (online). Report 3:T064. DOI: 10.1094/PDMR03.

Grella M, Marucco P, Balafoutis AT, Balsari P, 2020. Spray drift generated in vineyard during under-row weed control and suckering: Evaluation of direct and indirect drift-reducing techniques. Sustainability 12, 5068. doi:10.3390/su12125068.

Grossmann K, Kwiatkowski J, 1993. Selective induction of ethylene and cyanide biosynthesis appears to be involved in the selectivity of the herbicide quinclorac between rice and barnyard grass. Journal of Plant Physiology 142:457-466.

Grossman K, 1998. Quinclorac belongs to a new class of highly selective auxin herbicides. Weed Science 63:707-716.

Kalsing A, Rossi CVS, Lucio FR, Zobiole LHS, da Cunha LCV, Minozzi GB, 2018. Effect of formulations and spray nozzles on 2,4-D spray drift under field conditions. Weed Technology 32:379-384.

Kaminsk, JE, Fidanza MA, 2009. Dollar spot severity as influenced by fungicide mode of activity and spray nozzle. HortScience 44:1762-1766.

Koo SJ, Kwon YW, Cho KY, 1991. Differences in selectivity and physiological effects of quinclorac between rice and barnyard grass compared with 2,4-D. pp 103-111 in Proc. of the 13th Asian-Pacific Weed Society Conference, Jakarta, Indonesia.

Koo SJ, Neal JC, DiTomaso JM, 1997. Mechanism of action and selectivity of Quinclorac in grass
roots. *Pesticide Biochemistry and Physiology.* 57:44-53

Lake, JR, 1977. The effect of drop size and velocity on the performance of agricultural sprays. *Pesticide Science* 8:515-520.

Martin DP, Sullivan JJ, 1996. Influence of annual herbicide applications and the environment on smooth crabgrass control. *Proceedings of the Northeastern Weed Science Society* 50:114.

McCarty LB, Murphy T, Whitwell T, Yelverton F, 2005. Turfgrass weeds. pp 663-703 in McCarty LB (ed.), *Best golf course management practices.* 2nd ed. Prentice-hall, Upper Saddle River, NJ.

Mead R, Curnow RN, Hasted, AM, 2003. Statistical methods in agriculture and experimental biology, 3rd ed. CRC Press, Boca Raton, FL.

Johnson BJ, 1994. Influence of dates and frequency of Drive treatments on large crabgrass control in tall fescue turf. *Journal of Environmental Horticulture* 12:83-86.

Senseman SA, 2007. *Herbicide handbook.* Weed Science Society of America, Lawrence, KS

Stainier C, Destain M-F, Schifflers B, Lebeau F, 2006. Droplet size spectra and drift effect on two phenmedipham formulations and four adjuvants mixtures. *Crop Protection* 25(12):1238-1243.

Steinke K, Stier J, 2002. Tolerance of Supina bluegrass to pre- and post-emergence herbicides. *Journal of Environmental Horticulture* 20:118–121.

Watschke TL, Dernoeden PH, Shetlar DJ, 2013. *Managing turfgrass pests.* 2nd ed. CRC Press, Boca Raton, FL.

Woznica Z, Nalewaja J, Messersmith CG, Milkowski P, 2003. Quinclorac efficacy as affected by adjuvants and spray carrier water. *Weed Technology* 17:582-588.
Table 1. Spray nozzle, spray pattern, spray droplet size classification, and spray droplet size evaluated in the field studies in Wooster, Ohio, USA, and Reading, Pennsylvania, USA, 2020.

| Spray Nozzle            | Spray Pattern | Spray Droplet Classification | Spray Droplet Size volume mean diameter (µm)² |
|------------------------|---------------|------------------------------|---------------------------------------------|
| Delavan Raindrop 1/4   | hollow cone   | UC ultra coarse             | > 650                                       |
| TurfJet 1/4TTJO4       | flat fan      | EC extremely coarse         | 501 - 650                                  |
| Air Induction AA8004   | flat fan      | VC very coarse              | 401 - 500                                  |
| XR TeeJet 8015         | flat fan      | VC very coarse              | 401 - 500                                  |
| XR TeeJet 8008         | flat fan      | C coarse                    | 326 - 400                                  |
| GreenLeaf TDAD04       | dual flat fan | C coarse                    | 326 - 400                                  |
| XR TeeJet 8004         | flat fan      | M medium                    | 226 - 325                                  |
| XR TeeJet 8003         | flat fan      | F fine                      | 145 - 225                                  |

²The the volume mean diameter value represents 50% of the total volume of liquid spray comprised of droplets within diameters larger than the median value, and 50% smaller than the median value, for all nozzle types listed at 275 kPa application pressure.

Table 2. Analysis of variance for postemergence herbicide crabgrass (Digitaria sp.) efficacy data as influenced by spray nozzles from field studies in Wooster, Ohio, USA, and Reading, Pennsylvania, USA, 2020.

Ohio (USA)³

| Source of Variation³ | Degrees of Freedom | Mean Square | Prob (F) | Mean Square | Prob (F) | Mean Square | Prob (F) |
|----------------------|--------------------|-------------|----------|-------------|----------|-------------|----------|
| Replicate            | 3                  | 1194.707    | 0.0801   | 10.651      | 0.9327   | 115.539     | 0.1719   |
| Treatment            | 17                 | 176.407     | 0.0643   | 603.48      | 0.0001   | 40239.325   | 0.0001   |
| Error                | 51                 | 90.503      |          | 73.649      |          | 66.671      |          |

Pennsylvania (USA)³

| Source of Variation³ | Degrees of Freedom | Mean Square | Prob (F) | Mean Square | Prob (F) | Mean Square | Prob (F) |
|----------------------|--------------------|-------------|----------|-------------|----------|-------------|----------|
| Replicate            | 3                  | 0.257       | 0.1906   | 16.184      | 0.9023   | 0.722       | 0.0841   |
| Treatment            | 17                 | 0.026       | 0.1043   | 656.438     | 0.0001   | 1.972       | 0.0001   |
| Error                | 51                 | 0.016       |          | 84.883      |          | 0.308       |          |

³In Ohio, 9.16 kg quinclorac•ha⁻¹ + 1.75 L methylated seed oil•ha⁻¹ was applied on 24 Jun 2020 with average crabgrass was 24% plot area covered; majority of crabgrass was at the four leaf to one tiller stage.

³In Pennsylvania, 9.16 kg quinclorac•ha⁻¹ + 1.75 L methylated seed oil•ha⁻¹ was applied on 25 Jun 2020 with average crabgrass was 37% plot area covered; majority of crabgrass was at the four leaf to one tiller stage.

DAT = days after treatment.

Table 2. Analysis of variance for postemergence herbicide crabgrass (Digitaria sp.) efficacy data as influenced by spray nozzles from field studies in Wooster, Ohio, USA, and Reading, Pennsylvania, USA, 2020.

| Source of Variation³ | Degrees of Freedom | Mean Square | Prob (F) | Mean Square | Prob (F) | Mean Square | Prob (F) |
|----------------------|--------------------|-------------|----------|-------------|----------|-------------|----------|
| Replicate            | 3                  | 1194.707    | 0.0801   | 10.651      | 0.9327   | 115.539     | 0.1719   |
| Treatment            | 17                 | 176.407     | 0.0643   | 603.48      | 0.0001   | 40239.325   | 0.0001   |
| Error                | 51                 | 90.503      |          | 73.649      |          | 66.671      |          |

³In Ohio, 9.16 kg quinclorac•ha⁻¹ + 1.75 L methylated seed oil•ha⁻¹ was applied on 24 Jun 2020 with average crabgrass was 24% plot area covered; majority of crabgrass was at the four leaf to one tiller stage.

³In Pennsylvania, 9.16 kg quinclorac•ha⁻¹ + 1.75 L methylated seed oil•ha⁻¹ was applied on 25 Jun 2020 with average crabgrass was 37% plot area covered; majority of crabgrass was at the four leaf to one tiller stage.
Table 3. Postemergence herbicide crabgrass (*Digitaria* sp.) efficacy as influenced by spray droplet size from field studies in Wooster, Ohio, USA, and Reading, Pennsylvania, USA, 2020.

| Spray Nozzle and Droplet Sizea | Ohiob | Pennsylvaniac |
|-------------------------------|--------|---------------|
|                               | 24 Jun (0 DAT) | 23 Aug (60 DAT) | 23 Aug (60 DAT) | 25 Jun (0 DAT) | 24 Aug (60 DAT) | 24 Aug (60 DAT) |
|                               | % plot area covered | % control | % plot area covered | % control | % plot area covered | % control |
| Delavan Raindrop 1/4 UC       | 16 a  | 2 a           | 95 bc          | 24 a     | 31 bc           | 63 bc          |
| TurfJet 1/4TTJO4 EC           | 38 a   | 7 a           | 83 b           | 38 a     | 24 abc          | 71 bc           |
| Air Induction AA8004 VC       | 31 a   | < 1 a         | 98 c           | 21 a     | 12 a            | 86 c           |
| XR TeeJet 8015 VC             | 23 a   | < 1 a         | 98 c           | 40 a     | 17 ab           | 80 bc           |
| XR TeeJet 8008 C              | 27 a   | < 1 a         | 98 c           | 40 a     | 20 abc          | 76 bc           |
| GreenLeaf TDAD04 C            | 20 a   | 2 a           | 95 bc          | 43 a     | 21 abc          | 75 bc           |
| XR TeeJet 8004 M              | 14 a   | < 1 a         | 98 c           | 45 a     | 21 abc          | 75 bc           |
| XR TeeJet 8003 F              | 18 a   | < 1 a         | 98 c           | 38 a     | 35 c            | 58 b            |
| Untreated                     | 28 a   | 41 b          | 0 a            | 40 a     | 84 d            | 0 a            |

*Spray nozzle types, spray droplet sizes, and spray patterns:
Delavan Raindrop 1/4; UC (ultra coarse) = volume mean diameter (VMD) > 650 µm; hollow cone spray pattern
TurfJet 1/4TTJO4; EC (extremely coarse) = VMD 501-650 µm; flat fan spray pattern
Air Induction AA8004; VC (very coarse) = VMD 401-500 µm; flat fan spray pattern
XR TeeJet 8015; VC (very coarse) = VMD 401-500 µm; flat fan spray pattern
XR TeeJet 8008; C (coarse) = VMD 326-400 µm; flat fan spray pattern
GreenLeaf TDAD04; C (coarse) = VMD 326-400 µm; dual flat fan spray pattern
XR TeeJet 8004; M (medium) = VMD = 226-325 µm; flat fan spray pattern
XR TeeJet 8003; M (medium) = VMD = 145-225 µm; flat fan spray pattern.

bIn Ohio, 9.16 kg quinclorac•ha⁻¹ + 1.75 L methylated seed oil•ha⁻¹ was applied on 24 Jun 2020 with average crabgrass was 24% plot area covered; majority of crabgrass was at the four leaf to one tiller stage.

cIn Pennsylvania, 9.16 kg quinclorac•ha⁻¹ + 1.75 L methylated seed oil•ha⁻¹ was applied on 25 Jun 2020 with average crabgrass was 37% plot area covered; majority of crabgrass was at the four leaf to one tiller stage.

dDAT = days after treatment.

fPercent control calculated from plot ratings data as: \([\text{untreated} - \text{treated}] / \text{untreated}\) × 100.

fTreatment means followed by same letter are not statistically different according to Fisher’s protected least significance difference test at P ≤ 0.05.