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The Effect of Time of Day on the Activity of Postemergence Soybean Herbicides

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The effect of time of day (TOD) on the activity of six common POST herbicides was investigated in field trials from 2007 to 2009 at two locations in southwestern Ontario. Percentage weed control was assessed following application of bentazon, chlorimuron-ethyl, fomesafen, glyphosate, imazethapyr, or quizalofop-p-ethyl applied at 3-h intervals from 6:00 A.M. to midnight, when weeds averaged 15 cm tall. The effect of time of day varied with weed species, but weed control was generally reduced when herbicides were applied at 6:00 A.M., 9:00 P.M., and midnight. Herbicide activity on velvetleaf was most frequently reduced, especially for chlorimuron-ethyl, glyphosate, and imazethapyr. Control of common ragweed with glyphosate and imazethapyr was also affected by the timing of application, and pigweed species only showed an effect with glyphosate. Variation in temperature, relative humidity, and dew presence/absence at different times of the day, as well as morphological/physiological characteristics such as weed size at time of application and diurnal leaf movement in response to light intensity, may account for the variation in weed control at different times of the day. Significant soybean yield loss was not observed in this study, but may occur if herbicide efficacy is severely reduced by application at inappropriate times of day. These results provide valuable information for growers, and suggest that POST herbicides are most effective when applied midday, rather than in the early morning or late evening.
Nomenclature: Bentazon; chlorimuron-ethyl; fomesafen; glyphosate; imazethapyr; quizalofop-p-ethyl; common ragweed, *Ambrosia artemisiifolia* L. AMBEL; pigweed species, *Amaranthus* sp.; velvetleaf, *Abutilon theophrasti* Medic., ABUTH; soybean, *Glycine max* (L.) Merr.
Key words: Herbicide efficacy, time of day, POST herbicides, weed control.

El efecto del momento de aplicación durante el día (TOD) en la actividad de seis herbicidas POST comunes fue investigado en experimentos de campo desde 2007 a 2009 en dos localidades del suroeste de Ontario. El porcentaje de control de malezas fue evaluado después de la aplicación de bentazon, chlorimuron-ethyl, fomesafen, glyphosate, imazethapyr, o quizalofop-p-ethyl, aplicados en intervalos de 3 horas desde 6:00 A.M. hasta medianoche, cuando las malezas tuvieron una altura promedio de 15 cm. El efecto del momento de aplicación durante el día varió dependiendo de la especie de malezas, pero el control de malezas fue generalmente reducido cuando los herbicidas se aplicaron a 6:00 A.M., 9:00 P.M., y medianoche. La actividad herbicida se redujo más frecuentemente en *Abutilon theophrasti*, especialmente con chlorimuron-ethyl, glyphosate, e imazethapyr. El control de *Ambrosia artemisiifolia* con glyphosate e imazethapyr también fue afectado por el momento de aplicación, y las especies del género *Amaranthus* solamente mostraron efectos con glyphosate. Variaciones en temperatura, humedad relativa, y la presencia/ausencia de rocío en diferentes momentos del día, además de las características morfológicas/fisiológicas, tales como el tamaño de las malezas al momento de aplicación, y el movimiento diario de hojas en respuesta a la intensidad lumínica, podrían explicar la variación en el control de malezas en diferentes momentos del día. En este estudio, no se observaron pérdidas significativas en el rendimiento de la soya, pero estas podrían ocurrir si la eficacia del herbicida es reducida severamente debido a aplicaciones en momentos inapropiados durante el día. Los resultados brindan información valiosa para los productores, y sugieren que los herbicidas POST son más efectivos cuando son aplicados al mediodía, en lugar de las aplicaciones temprano en la mañana o tarde al final del día.

POST herbicides are a valuable component of integrated weed management strategies in agriculture. However, the efficacy of many POST herbicides has been demonstrated to vary dependent upon the time of day (TOD) they are applied. Such TOD effects regarding herbicide efficacy have been reported for bentazon (Andersen and Koukkari 1978; Doran and Andersen 1976), chlorimuron-ethyl (Miller et al. 2003), and fomesafen (Miller et al. 2003). A TOD effect has also been reported for glyphosate at below-label rates (Martinson et al. 2002; Miller et al. 2003; Mohr et al. 2007; Norsworthy et al. 1999; Sellers et al. 2003; Waltz et al. 2004); however, Stewart et al. (2009) suggested that TOD effects might be negated when a higher rate of glyphosate is used. To date, no studies have examined TOD effects on imazethapyr or quizalofop-p-ethyl, and few studies have focused on TOD effects in soybean [*Glycine max* (L.) Merr.] cropping systems. Therefore, additional data are required to determine if TOD effects for POST soybean herbicides exist.

Herbicide efficacy is often weed-species specific. Likewise, the effect of TOD on herbicide efficacy can also be weed-species specific. For example, in a flax (*Linum usitatissimum* L.) crop, fluazifop-P-butyl applied between 5:00 P.M. and 9:00 P.M. was observed to increase the control of green foxtail [*Setaria viridis* (L.) Beauv.], but the time of application had no effect on the control of wild oat (*Avena fatua* L.) (Fausey and Renner 2001). In southern Ontario, Stewart et al. (2009) reported species-specific TOD effects for atrazine, bromoxynil, dicamba/diflufenzopyr, glufosinate, glyphosate, and

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nicosulfuron when applied to barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), green foxtail, redroot pigweed (*Amaranthus retroflexus* L.), and velvetleaf (*Abutilon theophrasti* L.) in corn (*Zea mays* L.). In soybean field trials, Fausey and Renner (2001) reported species-specific TOD effects for fluthiacet-methyl and flumiclorac on the control of common lambsquarters and redroot pigweed, but not velvetleaf.

Several morphological and physiological factors may result in species-specific TOD effects for POST herbicides (Hess and Falk 1990). Weed size, leaf position (Andersen and Koukkari 1978; Doran and Andersen 1976; Mohr et al. 2007; Sellers et al. 2003), exposed leaf surface area (Kraatz and Andersen 1980), thickness of epicuticular wax (Hess and Falk 1990), and plant metabolic rate (Waltz et al. 2004) are all factors that may affect POST herbicide interception, absorption, and translocation (Stewart et al. 2009). Additionally, herbicide-specific factors such as mode of action (Miller et al. 2003), and environmental factors such as wind speed (Duke 2005; Waltz et al. 2004), the presence of dew (Fausey and Renner 2001; Kogan and Zúñiga 2001), air temperature (Doran and Andersen 1976; Friesen and Wall 1991; Kelley and Peeper 2003; Lee and Oliver 1982; Martinson et al. 2002; Ryneberg et al. 1992), and relative humidity (Coetzer et al. 2001; Johnson and Young 2002; Martinson et al. 2002; Sharma and Singh 2001) may influence POST herbicide application resulting in TOD effects.

Additional information with regards to potential TOD effects on POST herbicides applied in soybean is needed, because information pertaining to optimal TOD for application of these POST herbicides will be valuable to growers who seek to optimize weed control and maximize yields. Therefore, the objective of this research was to determine the optimal time of day to apply six common POST herbicides in soybean, to maximize weed control.

Material and Methods

Field trials were conducted at the University of Guelph Ridgetown Campus, Ridgetown, Ontario, from 2007 to 2009 and at the Agriculture and Agri-Food Canada, Greenhouse and Processing Crops Research Centre, Harrow, Ontario in 2009. The soil at Ridgetown was a clay loam with 36% sand, 31% silt, 33% clay, 4.2% organic matter, and a pH of 6.8 in 2007; a loam with 44.5% sand, 30.3% silt, 25.2% clay, 4.6% organic matter, and a pH of 7.3 in 2008; and a fine sandy loam with 56% sand, 24.1% silt, 19.9% clay, 3.8% organic matter, and a pH of 7.2 in 2009. The soil at Harrow was a sandy loam, with 61% sand, 27% silt, 12% clay, 2% organic matter, and a pH of 5.9 in 2009.

Procedures at Ridgetown and Harrow were the same unless otherwise noted. The soil was moldboard plowed in the fall, and the seedbed was prepared with two passes of an s-tine cultivator the following spring of each year. The herbicides tested were bentazon (840 g ai ha^{-1}); chlorimuron-ethyl (9 g ai ha^{-1}) plus a nonionic surfactant (0.2% v/v); fomesafen (240 g ai ha^{-1}) plus a nonionic surfactant (0.25% v/v); glyphosate (900 g ae ha^{-1}); imazethapyr (75 g ai ha^{-1}) plus a nonionic surfactant (0.25% v/v) plus 28% urea ammonium nitrate (UAN) (2 L/ha); and quizalofop-p-ethyl (36 g ai ha^{-1}) plus a surfactant/petroleum hydrocarbon blend (0.5% v/v). Glyphosate-tolerant soybean (2007 Dekalb 30-07R; 2008 Pioneer 30-07R; 2009 Dekalb 31-10R [Ridgetown] and Dekalb 32-60RY [Harrow]) were seeded at an average rate of 400,000 seeds/ha in rows spaced 76 cm apart. Individual plots were 2 by 10 m at Ridgetown and 2.25 by 8 m at Harrow.

Each experiment was established as a randomized complete block design with eight treatments and four replications for each herbicide at both locations. The eight treatments were herbicide application at 6:00 A.M., 9:00 A.M., noon, 3:00 P.M., 6:00 P.M., 9:00 P.M., midnight, and an untreated control. Herbicide treatments were applied when weeds averaged 15 cm in height. Herbicides were applied with the use of a CO_2-pressurized sprayer calibrated to deliver 200 L/ha (Ridgetown), and 222 L ha^{-1} (Harrow) aqueous solution at 207 kPa (Ridgetown), and 210 kPa (Harrow) with the use of ULD 120-02 nozzles spaced 50 cm apart.

Percent crop injury was assessed 1 and 48 wk after treatment (WAT), and weed control was assessed 4 and 8 WAT on a scale of 0 to 100%, where 0 was defined as no visible crop injury or weed control, and 100% was defined as complete weed control. The most prominent weed species at both locations were barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.], common lambsquarters (*Chenopodium album* L.), common ragweed (*Ambrosia artemisiifolia* L.), green foxtail [*Setaria viridis* (L.) Beauv.], pigweed species (*Amaranthus* sp.), and velvetleaf (*Abutilon theophrasti* L.). The weed control results from the 4-WAT assessment are presented here. Data from 8 WAT are not presented because some of the herbicides tested did not provide residual control, allowing flushes of new weeds to appear by 8 WAT regardless of the TOD effect. Soybean was mechanically harvested at maturity and threshed with the use of a plot combine. Yields were adjusted to a 13% moisture level.

All data were subjected to an analysis of variance (ANOVA) and analyzed with the use of the PROC MIXED procedure in SAS statistical software. Variances were partitioned into the fixed effect of TOD and into the random effect of environment (year and location), the interaction of environment by fixed effect, and blocks nested within environment. The assumptions of the variance analysis were tested by ensuring that the residuals were random, homogeneous, with a normal distribution about a mean of zero using residual plots, and the Shapiro-Wilk normality test. When the interaction between environment and TOD was not significant, data were pooled by environment. Percent weed control data were transformed with the use of square-root arcsine. Transformed data were backtransformed for presentation in tables. Comparison of treatment means were made with the use of Fisher's Protected LSD with a type I error set at 0.05. Further to this analysis, regression parameters were generated with the use of ANOVA by partitioning the treatment (time of day) mean squares into linear and quadratic polynomial components. The linear and quadratic components were then compared with the use of an F test, and the best-fit regression was chosen based on significance at a type-I error rate set at 0.05.

Results and Discussion

Weather Conditions. Weather conditions at the time of herbicide application varied by environment (Table 1). Air temperature and wind velocity were generally highest between noon and 6:00 P.M. Relative humidity was highest between 6:00 A.M. and 9:00 A.M. and again at midnight. Dew was commonly present at 6:00 A.M. and between 9:00 P.M. and midnight. Wind velocity was relatively low at Ridgetown and greatest at Harrow, but wind velocity did not exceed the recommended label maximums for the herbicides used in this study.

Time of Day Affects Herbicide Efficacy. Control of common ragweed, common lambsquarters, pigweed, and velvetleaf with bentazon was poor (< 70%) and variable throughout the day in this experiment. Similarly, control of common ragweed, lambsquarters, pigweed, and velvetleaf with fomasafen and quizalofop-p-ethyl was variable, and no TOD effect was observed (data not shown).

Weed control with chlorimuron-ethyl, glyphosate, and imazethapyr was species specific, with common ragweed, pigweed, and velvetleaf showing a significant TOD effect. Chlorimuron-ethyl provided 64 to 83% control of pigweed and 34 to 46% control of common ragweed (Figure 1). Chlorimuron-ethyl applied at noon provided 25% control of velvetleaf, and control was reduced by 16% at midnight. Application at 9:00 P.M. and midnight reduced velvetleaf control by 10 to 16%, respectively, when compared to control at noon.

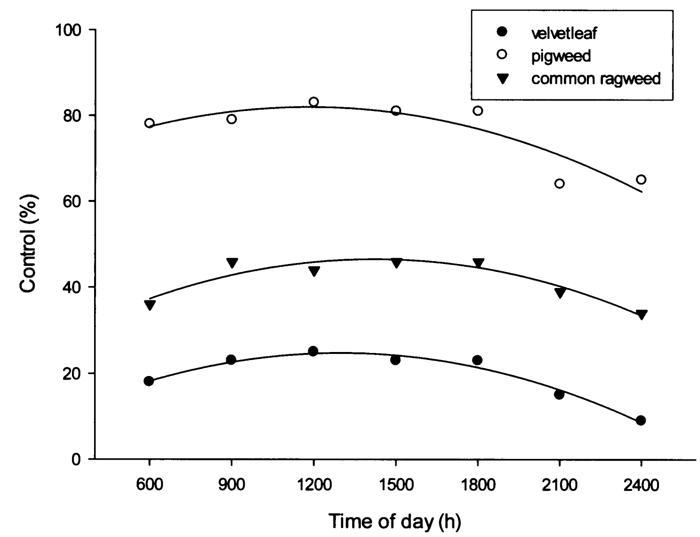

Figure 1. Mean percent weed control, 4 wk after treatment in response to chlorimuron-ethyl applied at different times during the day for velvetleaf ($Y = 2.2{+}0.03x - 0.00001x^2$, $R^2 = 0.97$, SE = 1.2); pigweed ($Y = 63.29 + 0.03x - 0.00001x^2$, $R^2 = 0.80$, SE = 4.3); and common ragweed ($Y = 18.8 + 0.04x - 0.00001x^2$, $R^2 = 0.88$, SE = 2.2) at Ridgetown, ON from 2007 to 2009 and at Harrow, ON in 2009. The best-fit regressions were chosen based on significance ($P < 0.05$) of an F test between linear and quadratic regression analysis with the use of ANOVA. Data were pooled by environment (location and year) when the interaction between environment and treatment was nonsignificant. SE = standard error of the model.

Table 1. Weather data at the time of herbicide application at Harrow, ON in 2009 and at Ridgetown, ON from 2007 to 2009.[a]

Application date	Time of day	Air temperature	Relative humidity	Wind velocity	Dew presence
	h	C	%	km h^{-1}	
Harrow					
June 26, 2009	6:00 A.M.	21.5	90	13.5	–
	9:00 A.M.	22.5	81	7.56	–
	Noon	25.1	61	13.2	–
	3:00 P.M.	27.3	51	12.3	–
	6:00 P.M.	27.3	41	10.4	–
	9:00 P.M.	24.6	60	8.85	–
	Midnight	19.3	70	5.63	–
Ridgetown					
June 25, 2007	6:00 A.M.	19.8	74	0.0	Y
	9:00 A.M.	23.7	56	1.1	N
	Noon	29.3	49	2.6	N
	3:00 P.M.	29.5	48	5.7	N
	6:00 P.M.	28.8	50	3.4	N
	9:00 P.M.	22.1	70	2.7	N
	Midnight	21.6	91	4.3	N
July 5, 2008	6:00 A.M.	14.1	85	0.0	Y
	9:00 A.M.	21.3	55	4.0	Y
	Noon	24.7	39	3.1	N
	3:00 P.M.	23.7	44	6.8	N
	6:00 P.M.	24.3	41	3.1	N
	9:00 P.M.	16.0	97	0.0	Y
	Midnight	13.1	100	0.0	Y
July 4, 2009	6:00 A.M.	11.4	100	1.2	Y
	9:00 A.M.	16.9	71	5.9	Y
	Noon	21.6	48	2.6	N
	3:00 P.M.	24.0	46	2.5	N
	6:00 P.M.	22.6	52	2.1	N
	9:00 P.M.	16.9	91	0.0	Y
	Midnight	16.1	99	1.0	Y

[a] Ridgetown weather data taken from the weather station at 42.45°N, 81.53°W; and Harrow weather data taken from the weather station at 42.03°N, 81.08°W. Abbreviations: Y, yes; N, no.

Glyphosate applied at Harrow controlled common ragweed, and velvetleaf at least 85%, and control did not differ throughout the day. However, TOD effects for glyphosate on common ragweed and velvetleaf were observed at Ridgetown (Figure 2). The control of velvetleaf at Ridgetown was highest (89%) when glyphosate was applied at noon, and lowest at 6:00 A.M., 9:00 P.M., and midnight, when control was reduced by up to 53%. A similar response was observed at Ridgetown, where glyphosate applied from 9:00 A.M. to 6:00 P.M. controlled 90 to 94% of common ragweed, but when applied at 6:00 A.M., 9:00 P.M., and midnight control was reduced by 20 to 41%. Regardless of location, glyphosate efficacy on pigweed was dependent on TOD.

Control of velvetleaf was best with imazethapyr between 9:00 A.M. and 6:00 P.M. with a maximum of 83% control observed when imazethapyr was applied at 3:00 P.M. (Figure 3). Velvetleaf control was reduced by 28 to 43% when imazethapyr was applied at 6:00 A.M., 9:00 P.M., or midnight in comparison to the observed maximum control at 3:00 P.M. Control of common ragweed was consistent throughout the day at Ridgetown; however, at Harrow common ragweed control was reduced in comparison to a peak at 3:00 P.M. before 9:00 A.M. and after 6:00 P.M. Imazethapyr provided a minimum of 65, 21, and 71% control for pigweed, common lambsquarters, and barnyard-

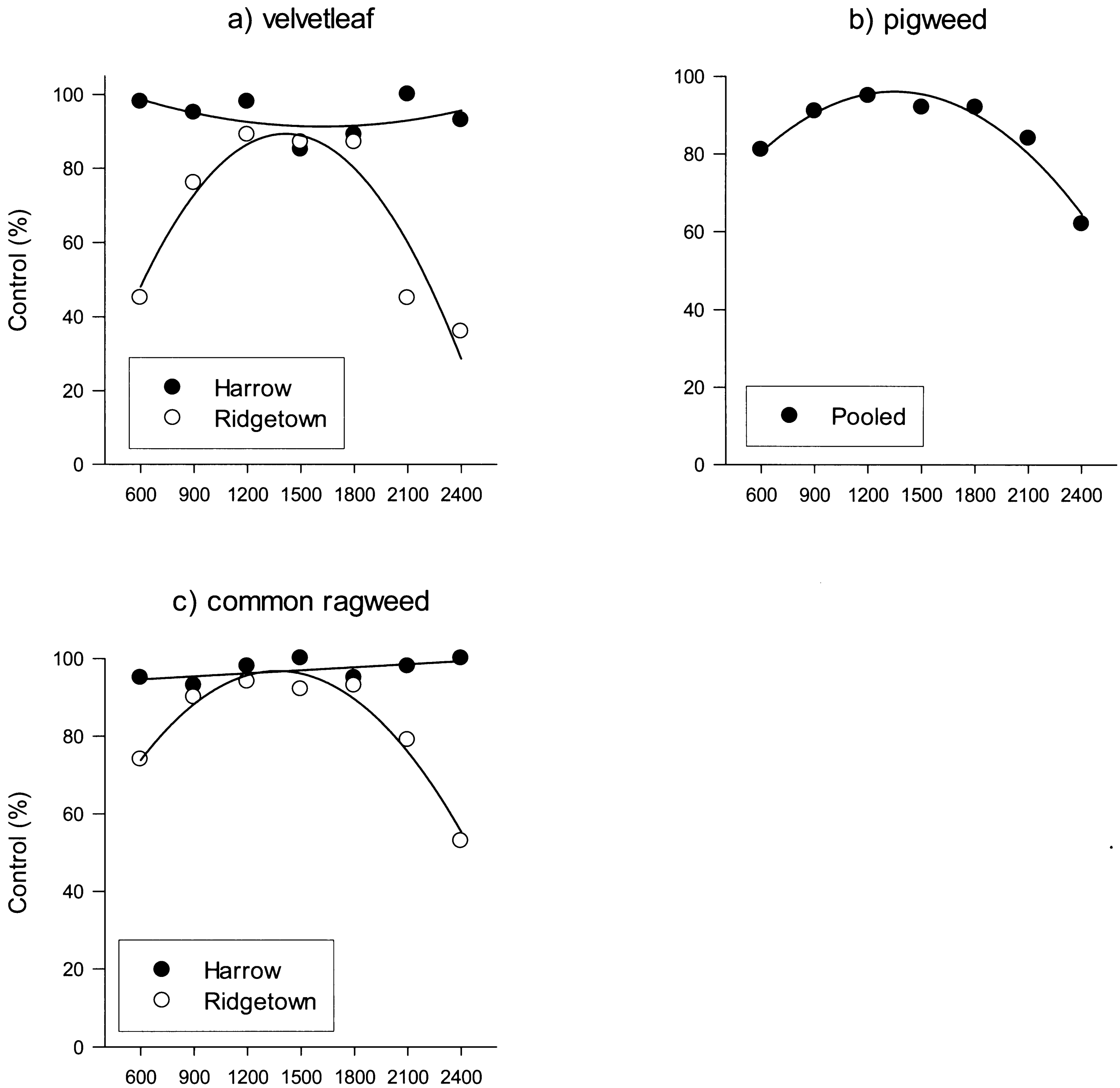

Figure 2. Mean percent weed control, 4 wk after treatment in response to glyphosate applied at different times during the day for (a) velvetleaf (Harrow, $Y = 110.0 + 0.02x - 0.00001x^2$, $R^2 = 0.24$, SE = 5.8; Ridgetown, $Y = -35.1 + 0.18x - 0.00001x^2$, $R^2 = 0.89$, SE = 9.4); (b) pigweed ($Y = 45.0 + 0.08x - 0.00001x^2$, $R^2 = 0.95$, SE = 3.1); and (c) common ragweed (Harrow, $Y = 110.0 + 0.02x - 0.00001x^2$, $R^2 = 0.40$, SE = 2.6; Ridgetown, $Y = -35.1 + 0.18x - 0.00001x^2$, $R^2 = 0.96$, SE = 3.5) at Ridgetown, ON from 2007 to 2009 and at Harrow, ON in 2009. The best-fit regressions were chosen based on significance ($P < 0.05$) of an F test between linear and quadratic regression analysis with the use of ANOVA. Data were pooled by environment (location and year) when the interaction between environment and treatment was nonsignificant. SE = standard error of the model.

grass, respectively, but control was not affected by TOD (data not shown).

Potential Factors Affecting Herbicide Efficacy. *Weed Size at Time of Application.* Weed size at time of application may have influenced herbicide efficacy in these trials, especially for the nonsystemic herbicides. Reduced weed control with the application of imazethapyr in soybean has previously been attributed to large weed size at time of application (Ateh and Harvey 1999). Weed size at the time of herbicide application averaged 15 cm, which may partially explain the variable weed

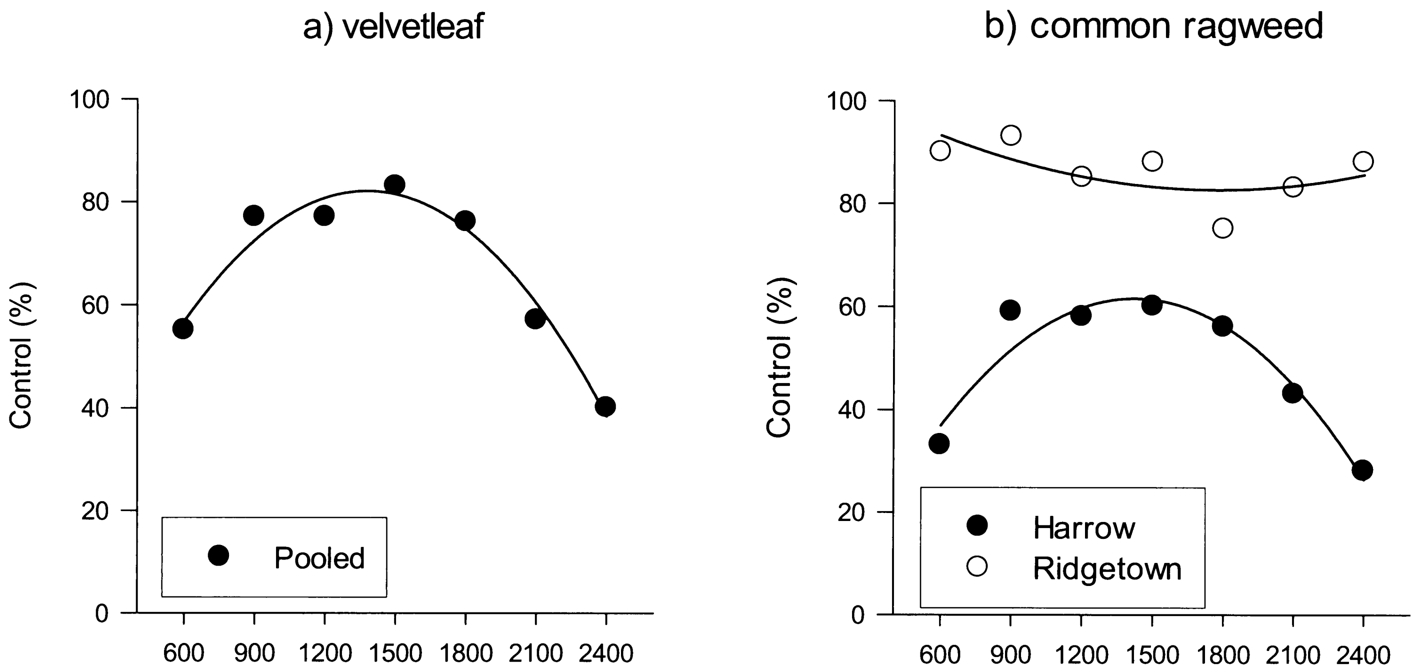

Figure 3. Mean percent weed control, 4 wk after treatment in response to imazethapyr applied at different times during the day for a) velvetleaf ($Y = 2.8 + 0.12x - 0.00001x^2$, $R^2 = 0.96$, SE = 3.7); and b) common ragweed (Harrow, $Y = -12.4 + 0.10x - 0.00001x^2$, $R^2 = 0.93$, SE = 4.5; Ridgetown, $Y = 106.9 - 0.03x - 0.00001x^2$, $R^2 = 0.89$, SE = 1.1) at Ridgetown, ON from 2007 to 2009 and at Harrow, ON in 2009. The best-fit regressions were chosen based on significance ($P < 0.05$) of an F-test between linear and quadratic regression analysis with the use of ANOVA. Data were pooled by environment (location and year) when the interaction between environment and treatment was nonsignificant. SE = standard error of the model.

control observed with the application of chlorimuron-ethyl, imazethapyr, and glyphosate on different weed species at each location.

Ambient Air Temperature. Similar to the results reported by Stewart et al. (2009) in corn, increased ambient air temperatures recorded at the time of POST herbicide application corresponded well with the TOD at which the highest weed control was recorded. Maximum air temperatures were observed between noon and 6:00 P.M. on the day of application in all environments (Table 1). This corresponds well with the optimal control of velvetleaf treated with chlorimuron-ethyl, glyphosate (at Ridgetown), and imazethapyr; pigweed treated with glyphosate; and common ragweed treated with glyphosate (at Ridgetown) and imazethapyr (at Ridgetown) between noon and 6:00 P.M. Previous studies have indicated that there is a relationship between increased ambient air temperature and improved herbicide efficacy (Doran and Andersen 1976; Lee and Oliver 1982; Madafiglio et al. 2000; Sharma and Singh 2001). Increased air temperature is thought to alter leaf cuticular wax (Hess and Falk 1990; Willingham and Graham 1988) and increase cuticle and plasma membrane fluidity, resulting in improved herbicide uptake and translocation (Johnson and Young 2002).

Leaf Angle and Photosynthetic Photon Flux. Although it was not measured in this study, past studies have indicated that herbicide efficacy increases with alteration of leaf angle and an associated increase in light intensity or photosynthetic photon flux density (PPFD) (Andersen and Koukkari 1978; Norsworthy et al. 1999). Velvetleaf exhibits diurnal leaf movements where leaves are near-vertical in reduced light (Andersen and Koukkari 1978), potentially reducing spray interception of foliar-applied herbicides, glyphosate in particular (Martinson et al. 2002; Mohr et al. 2007; Norsworthy et al. 1999; Waltz et al. 2004). As a result, it may be possible to attribute TOD effects such as those observed in this study, to the vertical orientation of leaves in the morning and evening when herbicide efficacy was lowest.

Presence of Dew. The presence of dew on the leaves of target plants may increase runoff and/or dilution of foliar-applied herbicides, resulting in poor weed control (Doran and Andersen 1976). In species such as velvetleaf that have leaf surfaces covered in trichomes, dew may be held on the leaves, reducing contact of foliar herbicides with the leaf surface (Sanyal et al. 2006). However, some studies have found that low herbicide spray volumes may decrease runoff and enhance foliar uptake regardless of dew presence (Johnson and Young 2002).

Time-of-Day Effects on Soybean Yield. Despite TOD effects being determined for some weed species with the application of chlorimuron-ethyl, glyphosate, and imazethapyr, final crop yield was not significantly affected by TOD of application (data not shown). However, soybeans did show a 15% reduction in yield when glyphosate was applied at 6:00 A.M. and midnight in comparison to the weed-free control, which could result in financial loss. However, when glyphosate was applied between 9:00 A.M. and 6:00 P.M. yields did not differ from the weed-free control. Crop injury was not observed in this study for any treatment (data not shown), suggesting that any reduction in crop yields were a result of interspecific competition from weeds that escaped control of the herbicides.

This study has shown that POST herbicides commonly applied in soybean crops can be affected by TOD of application. The TOD effects observed in this study were species specific, with velvetleaf showing particular sensitivity to TOD when chlorimuron-ethyl, glyphosate, and imazethapyr were applied. Early-morning applications at 6:00 A.M. and late-evening applications at 9:00 P.M. and midnight showed reduced weed control compared to when those herbicides were applied to velvetleaf between 9:00 A.M. and 6:00 P.M. Common ragweed responded with a similar TOD effect when treated with glyphosate and imazethapyr, as did pigweed treated with glyphosate. Environmental factors such as temperature at time of application, as well as morphological and physiological factors such as diurnal leaf movements, are likely responsible for the TOD effects observed in this study. Although TOD effects were not observed for some species, all herbicides tested in this study provided the best weed control when applied between 9:00 A.M. and 6:00 P.M. The TOD effects observed did not affect the final yield of soybean in this study; however, insufficient weed control resulting from poorly timed application has the potential to reduce yield. These data suggest that farmers should apply POST herbicides in soybean at midday rather than early morning or late evening, in order to avoid potential TOD effects.

Acknowledgments

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