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Weed Technology

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Impact of delayed postemergence herbicide application on corn yield based on weed height, days after emergence, accumulated crop heat units, and corn growth stage

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Research Article

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Abstract

Nine field experiments were conducted from 2017 to 2019 in Ontario to determine the impact of early weed interference on corn yield based on corn growth stage, days after emergence (DAE), accumulated crop heat units (CHU), and weed size. The predicted weed size at herbicide application that resulted in a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn was estimated to be 1, 4, 11, 53, non-estimable (N est.*), and N est.* cm under low weed density and 3, 5, 7, 11, 27, and N est.* cm under high weed density, respectively. The predicted DAE at herbicide application time that resulted in a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn was predicted to be 14, 20, 27, 44, N est.*, and N est.* DAE under low weed density and 5, 7, 11, 17, 25, and 59 DAE under high weed density, respectively. The predicted CHU from planting at herbicide application time that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn was 468, 636, 821, 1,271, N est.*, and N est.* CHU from planting under low weed density and 207, 283, 385, 551, 972, and 1,748 CHU from planting under high weed density, respectively. The predicted crop stage at herbicide application that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn was V5, V6, V7, V11, N est.*, and N est.* under low weed density and V1, V2, V3, V4, V8, and V14 under high weed density, respectively. Results indicate that weeds must be controlled before they reach 7 cm in height, prior to 11 d after crop emergence, prior to 385 accumulated CHU from emergence, or prior to the V3 stage under high weed density to avoid greater than 5% yield loss.

Introduction

Corn is one of the most widely grown grain crops globally (Shahbandeh 2021). Corn originated more than 7,000 years ago as a wild grass in Mexico and has now become one of the most important food crops globally (Daynard 2019; Wallace and Brown 2020). In 2020–2021, Canada is among the top 12 countries in corn production, having produced nearly 14 billion kg of corn (Shahbandeh 2021). Ontario farmers grow most of the corn produced in Canada. In 2020, producers in Ontario planted almost 900,000 ha and produced almost 9 billion kg of corn with a value of nearly Can$1.8 billion (OMAFRA 2021). Corn is sensitive to early weed interference. The yield loss committee of the Weed Science Society of America (WSSA) reported an average corn yield loss of 50% if weeds are left uncontrolled (Soltani et al. 2016).

An understanding of the critical weed-free period (CWFP) is vital for the development of integrated weed management programs in corn (Hall et al. 1992; Swanton and Weise 1991). The CWFP is commonly known as the time period in the development of the crop when weeds must be controlled beyond which irreversible crop yield losses occur (Hall et al. 1992; Knezevic et al. 2002; Tursun et al. 2016). The beginning of the CWFP is determined using the critical time of weed removal (CTWR), whereas the end of the CWFP is determined using the CWFP (Knezevic et al. 2002). Thus, weed control measures that are too early or too late and do not fall within the CWFP have limited advantages in obtaining optimum crop yield (AAFC 2021). The optimal time to control weeds is field-specific and is influenced by weed species composition, weed density, competitive indices of each weed species, the relative time of weed and crop emergence, tillage practices, crop row spacing, nutrient availability, and environmental factors (AAFC 2021; Arslan et al. 2006; DiTomaso 1995; Evans et al. 2003; Knezevic et al. 2002; Mohammadi and Amiri 2011; Zimdahl 1980). The CWFP and CTWR have been determined based on a function of several factors including weed size, planting date, days after crop emergence (DAE), accumulated heat units (CHU) from emergence, crop growth stage, nitrogen application date, and other variables (Bedmar et al. 1999; Evans et al. 2003; Hall et al. 1992; Swanton et al. 1991; Tursun et al. 2016; Williams 2006).

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An earlier study by Hall et al. (1992) in Ontario concluded that the CWFP in corn is 3 to 14 corn leaf tips. Norsworthy and Oliveira (2004) reported a CWFP of 5 to 9 DAE (1- to 2-leaf corn) to 45 to 53 DAE (8- to 10-leaf corn) at sites with high weed density. However, at other sites with lower weed density, the CWFP was 4 to 21 DAE (5-leaf corn) to 25 DAE (5- to 6-leaf corn). Tursun et al. (2016) studied the CWFP in three corn types (field corn, popcorn, and sweet corn) and found that weed control must be started around the V1 growth stage, and corn must be maintained weed-free up to the V12 growth stage to avoid >5% yield loss in all corn types. Bedmar et al. (1999) used accumulated CHU to describe the CWFP in corn and found that weeds had to be controlled from 222 to 416 CHU and 128 to 261 CHU to prevent yield losses of 2.5%.

Corn hybrids have advanced in recent years to have morphological traits for better weed suppressive characteristics through enhanced early growth, greater shoot biomass, increased plant height, and earlier flowering (Daynard 2019). The weed suppression capability of these new corn hybrids may influence the impact of early-season weed interference, influence the CTWR, affect the length of the CWFP, and result in yield benefits for corn production (Daynard 2019). Nearly all of the earlier CWFP and specifically CTWR studies completed in Ontario were done with glyphosate-susceptible (GS) corn (Hall et al. 1992; Swanton and Weise 1991). Most of the corn hybrids used in Ontario are currently glufosinate-, and glyphosate-resistant hybrids (Soltani et al. 2014). Corn production practices have changed considerably over the past two decades with earlier planting dates, higher seeding rates, and increased nitrogen application rates, all of which could potentially affect the start of the CWFP in corn. Additionally, the early planting dates may have shifted weed species community composition and density, which in turn may have caused a shift in the CWFP and CTWR.

There is little current information on the CWFP and CTWR in corn in Ontario. Such information is vital for corn growers to manage weeds at the appropriate time in corn development to maximize yield and net returns. The purpose of this study was to determine the CTWR in corn under environments of low and high weed density based on weed size, DAE, accumulated CHU from planting, and corn growth stage.

Materials and Methods

A study consisting of nine field experiments was conducted during 2017 to 2019 at Exeter (43.316305° N, 81.504763° W) (for two experiments in 2017, three in 2018, and one in 2019) and Ridgetown (42.444594° N, 81.883203° W) (for two experiments in 2017 and one in 2018) in Ontario. Seedbed preparation at all sites consisted of fall moldboard plowing followed by two passes with a field cultivator with rolling-basket harrows in the spring.

Experiments were arranged in a randomized complete block design with four replications. Experiments included a weedy control, a weed-free control, and six postemergence treatments where the first herbicide application (glyphosate at 900 g ae ha^{-1}) was made when weeds were 5, 10, 15, 20, 30, and 50 cm in height. All treatments were maintained weed-free until harvest after the first herbicide application.

Each plot was 3 m wide and 10 m long at Exeter and 8 m long at Ridgetown and consisted of four rows (0.75 m apart) of corn (glyphosate/glufosinate-resistant) seeded at approximately 80,000 seed ha^{-1} in May of each year. All plots were fertilized according to recommended Ontario crop production practices.

Glyphosate was applied with a CO_2-pressurized backpack sprayer calibrated to deliver 200 L ha^{-1} of water at 200 kPa. The boom was 1.5 m long with four nozzles (Hypro ULD120-02 nozzle tips; Pentair-Hypro Inc, New Brighton, MN) spaced 0.5 m apart producing a spray width of 2.0 m.

Corn was harvested (two center rows) at maturity using a small-plot combine. Yields were adjusted to 15.5% seed moisture and converted to kg ha^{-1}. The yield was converted to a percent of the weed-free control to standardize yield.

Data were analyzed using PROC NLIN in SAS 9.4 (SAS Institute Inc., Cary, NC). The response variable, corn yield relative to the weed-free control, was regressed against initial herbicide application timing, expressed as four individual explanatory variables (EVARs): weed size, days after crop emergence, CHU accumulated from planting, or crop stage. Weed size, the average weed canopy height in a mixed weed population, was the experimental trigger for herbicide applications. Weed size was not measured after the last application, and therefore the relative yield of the weedy control could not be included for this EVAR. Days after crop emergence was simply the difference in days between corn emergence and each application date; the weed-free control was given a value of 0, and the weedy control was represented by the number of days to reach physiological maturity, reflecting the season-long presence of weeds. The CHU accumulated (Bedmar et al. 1999) from planting date to each application date was determined from daily data obtained from the nearest weather station (Ridgetown and Exeter, ON), and the weedy control was assigned a CHU corresponding to the hybrid maturity rating. The crop stage was recorded at the time of each application, and each stage was assigned a numerical value: 0 for the preemergence application on the weed-free control, 1 for V1, up to 24 or 25 for physiological maturity, corresponding to the weedy control.

Prior to regression analysis, scatterplots of the data were examined to determine potential models worth evaluating. From the scatterplots, it appeared that the yield response for two environments differed from the other seven environments. An obvious difference between the two groups of environments was the overall weed density: two environments had lower weed densities, ranging from 12 to 82 weeds m^{-2} at individual application timings and averaging 57 weeds m^{-2} for the season, whereas the other seven environments had higher weed densities, ranging from 132 to 411 weeds m^{-2} at individual application timings and averaging 148 to 353 weeds m^{-2}. The weed population was a mix of broadleaves and grasses; therefore, total weed density was utilized. Environment-by-EVAR interactions obtained from Proc Glimmix was used to check the consistency in response for all environments combined, and for the two groups of environments separately. When all environments were pooled, the P values ranged from <0.0001 to 0.016, indicating that responses were not consistent. However, P values, when two groups of environments were separated, ranged from 0.043 to 0.48, indicating much more consistent responses within each group. This was further confirmed during regression analysis by comparing calculated Akaike information criterion (AIC) values for all environments pooled together versus separating environments into two groups based on weed density; for all EVARs, AIC values were substantially lower for the latter scenario.

Potential regression models based on examination of the data scatterplots included a four-parameter log-logistic model for both the lower and higher weed density groups and a linear model for

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Table 1. Parameter estimates and predicted values for relative corn yield regressed against initial herbicide application timing expressed in terms of weed size, days after crop emergence (DAE), CHU accumulated from planting (CHUpl), or crop stage as explanatory variables (EVARs). Nine experiments, conducted at Ridgetown Campus, Ridgetown, ON (2017–2019) and the Huron Research Station, Exeter, ON (2017–2018), were separated into two groups, lower (LD) and higher (HD) weed densities, for analysis.[a]

		Parameter estimates[b]										Predicted EVAR value[c]					
EVAR	Group	*C*		*D*		*b*		I_{50}		ME	RMSE	YL_1	$YL_{2.5}$	YL_5	YL_{10}	YL_{25}	YL_{50}
Weed size in cm	LD	100	(2)	87	(11)	1.1	(1.2)	18	(32)	0.51	4.6	1	4	11	53	–	–
	HD	100	(2)	66	(5)	2.1	(0.6)	16	(3)	0.89	9.5	3	5	7	11	27	–
DAE	LD	100	(2)	87	(2)	3.6	(1.7)	31	(5)	0.41	4.5	14	20	27	44	–	–
	HD	101	(2)	0	(0)	1.6	(0.1)	67	(4)	0.79	11.7	5	7	11	17	25	59
CHUpl	LD	100	(2)	87	(2)	4.0	(1.9)	927	(130)	0.38	4.8	468	636	821	1,271	–	–
	HD	101	(2)	0	(0)	1.8	(0.1)	1,729	(89)	0.79	11.9	207	283	385	551	972	1,748
Crop stage[d]	LD	100	(2)	88	(2)	4.7	(2.2)	8	(1)	0.40	4.7	5	6	7	11	–	–
	HD	100	(2)	0	(0)	1.7	(0.1)	14	(1)	0.78	12.1	1	2	3	4	8	14

[a]Abbreviations: ME, modeling efficiency; RMSE, root mean square error.
[b]Log-logistic equation parameters (Equation 1): *b*, slope; *C*, upper asymptote; *D*, lower asymptote; I_{50}, EVAR value required for 50% response. Figures in parentheses are ±SE.
[c]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50} are the values of an EVAR that result in a 1%, 2.5%, 5%, 10%, 25%, and 50% loss in corn yield, relative to the season-long weed-free control A dash indicates that the value in question was non-estimable because the asymptote was reached prior to that particular level of yield loss.
[d]Sequential numeric values assigned to vegetative and reproductive corn stages: 0 = preemergence, 1 = V1 . . . 17 = V17, 24/25 = R7.

the lower weed density group only. Regression analysis was carried out in SAS 9.4 using Proc NLIN, and residual plots were checked to make sure assumptions were met. The root means square error (RMSE) and modeling efficiency (ME), as well as plots of actual versus predicted values, were used to assess the goodness of fit for the models evaluated. For the lower weed density group, the four-parameter log-logistic model was superior to the linear model for all EVARs, based on residual plots, the goodness of fit, and calculated AICc values. The log-logistic model used to regress relative corn yield against herbicide application timing expressed as each EVAR, was:

$$Y = C + (D - C)/(1 + \exp[-b\,(\ln \text{EVAR} - \ln I_{50})]) \quad [1]$$

where *C* is the upper asymptote, *D* is the lower asymptote, *b* is the slope, and I_{50} is the value of an EVAR that gives a response halfway between *C* and *D*. Predicted values of each EVAR that gave a 1%, 2.5%, 5%, 10%, 25%, and 50% reduction in yield, relative to the weed-free control, were calculated using the regression equations. The "N est*" abbreviation was used to indicate that the value in question was non-estimable because the asymptote was reached prior to that particular level of yield loss.

Results and Discussion

At Exeter, weed species composition included green foxtail (*Setaria viridis* L. Beauv.), wild mustard (*Sinapis arvensis* L.), common lambsquarters (*Chenopodium album* L.), flower-of-an-hour (*Hibiscus trionum* L.), redroot pigweed (*Amaranthus retroflexus* L.), smartweed (*Polygonum scabrum* Moench.), wild buckwheat (*Polygonum convolvulus* L.), ladysthumb (*Polygonum persicaria* L.), and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv.]. In Ridgetown, weed species composition consisted of green foxtail, barnyardgrass, common lambsquarters, velvetleaf, common ragweed (*Ambrosia artemisiifolia* L.), and pigweeds.

Relative corn yield decreased as a function of weed size at the time of herbicide application. The weed size at the application time that resulted in a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn, relative to the season-long weed-free control was 1, 4, 11, 53, N est.*, and N est.* cm under low weed density and 3, 5, 7, 11, 27, and N est.* cm under high weed density, respectively (Table 1; Figure 1).

Relative corn yield was decreased as a function of days after crop emergence (DAE) at the time of postemergence herbicide application. The DAE at application time that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn, relative to the season-long weed-free control was 14, 20, 27, 44, N est.*, and N est.* DAE under low weed density and 5, 7, 11, 17, 25, and 59 DAE under high weed density, respectively (Table 1; Figure 2). Bedmar et al. (1999) calculated that the CWFP to prevent 2.5% yield loss in corn was 8 to 30 DAE. Norsworthy and Oliveira (2004) reported that the CWFP was between 5 and 9 DAE (1- to 2-leaf corn) to 45 to 53 DAE (8- to 10-leaf corn) at the site with higher weed density. However, at other sites with lower weed density, the CWFP was only 4 d, from 21 DAE (5-leaf corn) to 25 DAE (5- to 6-leaf corn). Mahmoodi and Rahimi (2009) reported that the CWFP to prevent 2.5%, 5%, 10%, and 20% yield loss in corn was 14 to 59 DAE, 19 to 55 DAE, 25 to 47 DAE, and 31 to 36 DAE, respectively. Isik et al. (2006), using a fitting logistic and Gompertz equation, determined that the CWFP for a 5% yield loss in corn was 0.2 to 5.2 wk after emergence (1- to 2-leaf corn).

Relative corn yield was decreased as a function of CHU accumulated from planting at the time of herbicide application. The CHU from planting at application time that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn, relative to the season-long weed-free control, was 468, 636, 821, 1,271, N est.*, and N est.* CHU from planting under low weed density and 207, 283, 385, 551, 972, and 1,748 CHU from planting under high weed density, respectively (Table 1; Figure 3). In other studies, Bedmar et al. (1999) calculated the CWFP to prevent 2.5% yield loss in corn varies between 128 and 416 CHU.

Relative corn yield was decreased as a function of crop stage at the time of herbicide application. The crop stage that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn, relative to the season-long weed-free control, was V5, V6, V7, V11, N est.*, and N est.* under low weed density and V1, V2, V3, V4, V8, and V14 under high weed density, respectively (Table 1; Figure 4). Hall et al. (1992) reported that the beginning of CWFP varied from the 3- to 14-leaf stage (V1 to V12) in corn under Ontario environmental conditions. Tursun et al. (2016), studying the CWFP in three corn types (field corn, popcorn, and sweet corn), found that weed control must be started around the V1 stage and maintained weed-free up to the V12 stage to avoid >5% yield losses in all corn types. Bedmar et al. (1999) calculated

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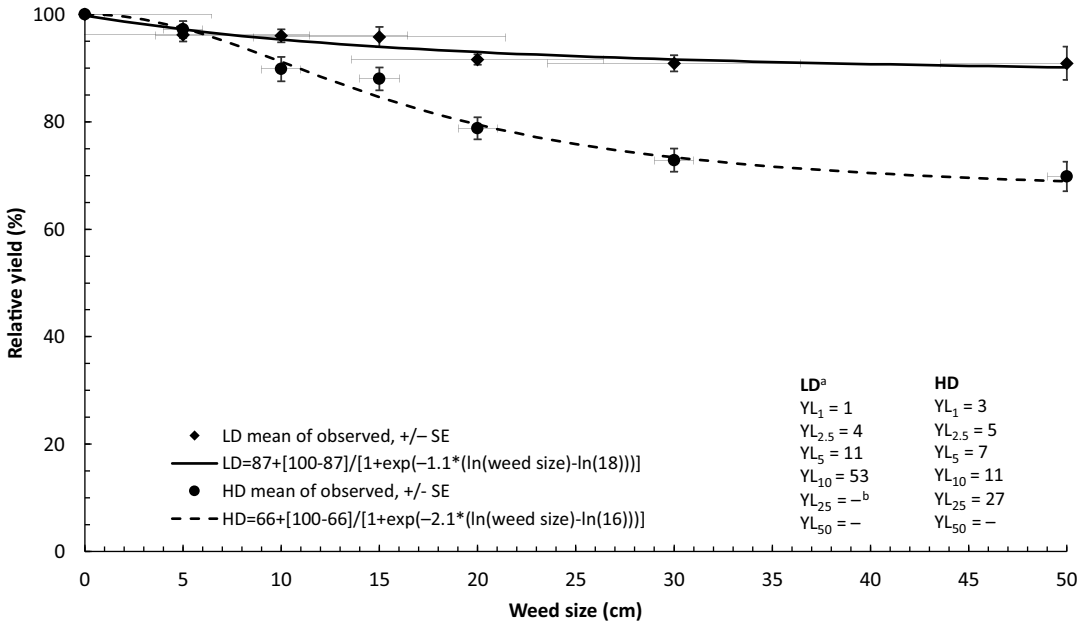


Figure 1. Relative corn yield as a function of weed size at the time of herbicide application. Nine experiments, conducted at Ridgetown Campus, Ridgetown, ON (2017–2019) and the Huron Research Station, Exeter, ON (2017–2018), were separated into two groups, lower (LD, 12 to 82 weeds m^{-2}) and higher (HD, 132 to 411 weeds m^{-2}) weed densities. Predicted regression lines were calculated using the log-logistic model (Equation 1). LD ME = 0.51, RMSE = 4.6; HD ME = 0.89, RMSE = 9.5. [a]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50}: weed size at the application that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn, relative to the season-long weed-free control. [b]Non-estimable. ME, modeling efficiency; RMSE, root mean square error.

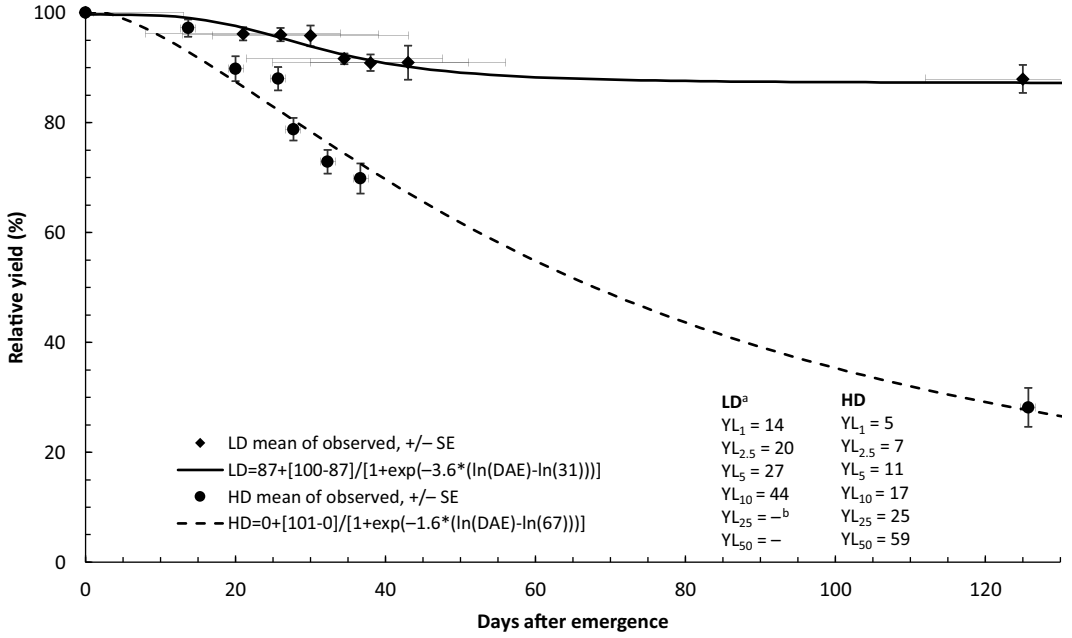


Figure 2. Relative corn yield as a function of days after crop emergence at the time of herbicide application. Nine experiments, conducted at Ridgetown Campus, Ridgetown, ON (2017–2019) and the Huron Research Station, Exeter, ON (2017–2018), were separated into two groups, lower (LD, 12 to 82 weeds m^{-2}) and higher (HD, 132 to 411 weeds m^{-2}) weed densities. Predicted regression lines were calculated using the log-logistic model (Equation 1). LD ME = 0.41, RMSE = 4.5; HD ME = 0.79, RMSE = 11.7. [a]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50}: days after emergence at the application that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn, relative to the season-long weed-free control. [b]Non-estimable. ME, modeling efficiency; RMSE, root mean square error.

that the CWFP to prevent 2.5% yield loss in corn varies between 5- and 7-leaf corn (V3 to V5). Mahmoodi and Rahimi (2009) reported that the CWFP to prevent 2.5%, 5%, 10%, and 20% yield loss in corn was 4- to the17-leaf stage (V2 to V15), 5- to 15-leaf stage (V3 to V13), 6- to 12-leaf stage (V4 to V10), and 8- to the 9-leaf stage (V6 to V7), respectively.

This study shows that substantial corn yield losses can occur as the timing of initial weed control is delayed. The relative corn yield was decreased with increased weed size, DAE, CHU from the planting, and corn growth stage. Generally, the variables measured (weed size, DAE, CHU, and crop stage) predicted a similar yield loss pattern in corn. The CTWR was much earlier under higher

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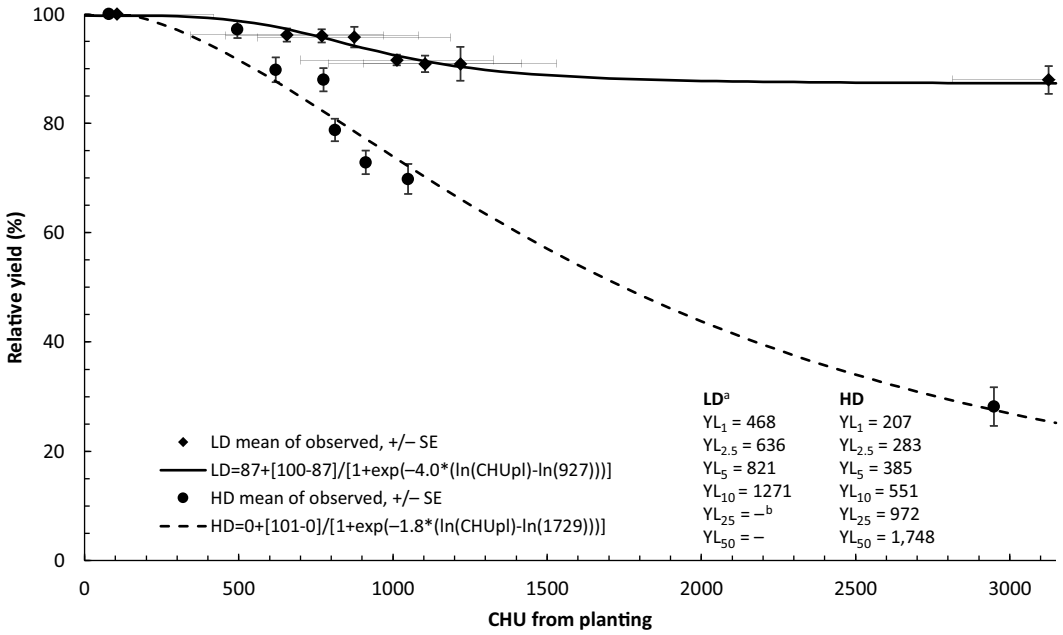


Figure 3. Relative corn yield as a function of CHU accumulated from planting at the time of herbicide application. Nine experiments, conducted at Ridgetown Campus, Ridgetown, ON (2017–2019) and the Huron Research Station, Exeter, ON (2017–2018), were separated into two groups, lower (LD, 12 to 82 weeds m^{-2}) and higher (HD, 132 to 411 weeds m^{-2}) weed densities. Predicted regression lines were calculated using the log-logistic model (Equation 1). LD ME = 0.38, RMSE = 4.8; HD ME = 0.79, RMSE = 11.9. [a]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50}: accumulated CHU at the application that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn, relative to the season-long weed-free control. [b]Non-estimable. ME, modeling efficiency; RMSE, root mean square error.

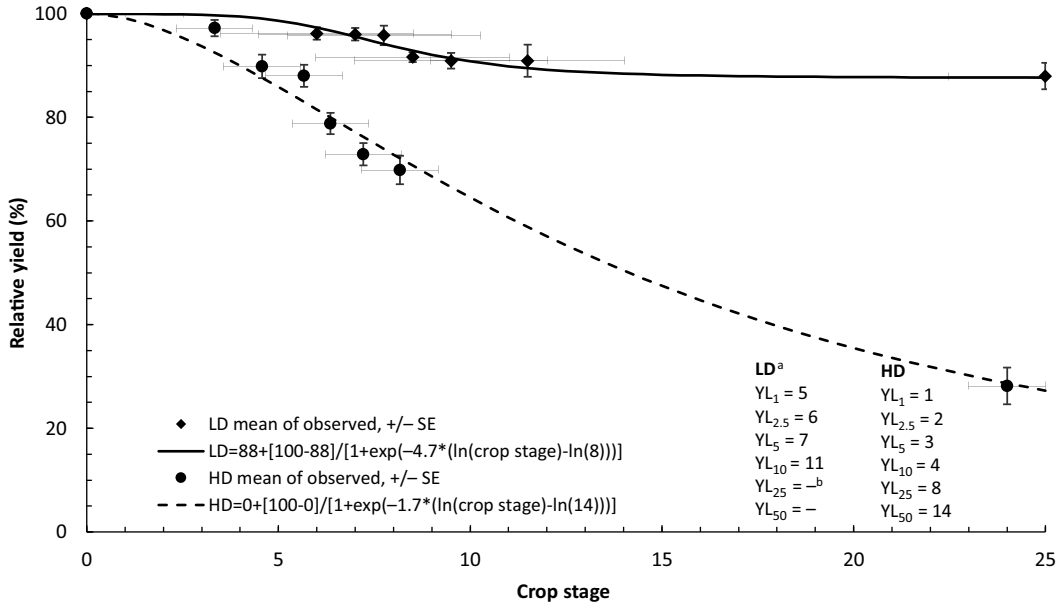


Figure 4. Relative corn yield as a function of crop stage at the time of herbicide application. Nine experiments, conducted at Ridgetown Campus, Ridgetown, ON (2017–2019) and the Huron Research Station, Exeter, ON (2017–2018), were separated into two groups, lower (LD, 12 to 82 weeds m^{-2}) and higher (HD, 132 to 411 weeds m^{-2}) weed densities. Predicted regression lines were calculated using the log-logistic model (Equation 1). LD ME = 0.4, RMSE = 4.7; HD ME = 0.78, RMSE = 12.1. [a]YL_1, $YL_{2.5}$, YL_5, YL_{10}, YL_{25}, and YL_{50}: crop stage at the application that led to a 1%, 2.5%, 5%, 10%, 25%, and 50% yield loss in corn, relative to the season-long weed-free control. [b]Non-estimable. [c]Sequential numeric values assigned to vegetative and reproductive corn stages: 0 = preemergence, 1 = V1 . . . 17 = V17, 24/25 = R7. ME, modeling efficiency; RMSE, root mean square error.

weed density compared to the lower weed density. To cause a 5% corn yield reduction, the average weed size was predicted to be 11 cm under low weed density and 7 cm under high weed density. The number of days that led to a 5% yield reduction in corn was 27 DAE under low weed density and only 11 DAE under high weed density. Similarly, the CHU from planting that led to a 5% yield reduction in corn was 821 CHU from planting under low weed density and only 385 CHU from planting under high weed density. If the weeds were not controlled until V5, V6, V7, and V11, it is predicted that there would be a 1%, 2.5%, 5%, and 10% reduction in corn yield under low weed density, respectively. However, when the weed density was high, it was predicted that corn yield can be reduced by 1%, 2.5%, 5%, 10%, 25%, and 50% if weeds were not controlled at V1, V2, V3, V4, V8, and V14, respectively. These

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results reaffirm the sensitivity of corn to early weed interference and the importance of timely postemergence herbicide application. Results showed that corn weed control must be initiated at the V3 stage when the field has high weed density and V7 when the field has low weed density to avoid greater than 5% yield loss.

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