Estimation of Critical Period for Weed Control in Corn in Iran

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***Abstract*—**The critical period for weed control (CPWC) is the period in the crop growth cycle during which weeds must be controlled to prevent unacceptable yield losses. Field studies were conducted in 2005 and 2006 in the University of Birjand at the south east of Iran to determine CPWC of corn using a randomized complete block design with 14 treatments and four replications. The treatments consisted of two different periods of weed interference, a critical weed-free period and a critical time of weed removal, were imposed at V_3, V_6, V_9, V_{12}, V_{15}, and R_1 (based on phonological stages of corn development) with a weedy check and a weed-free check. The CPWC was determined with the use of 2.5, 5, 10, 15 and 20% acceptable yield loss levels by non-linear Regression method and fitting Logistic and Gompertz nonlinear equations to relative yield data. The CPWC of corn was from 5- to 15-leaf stage (19-55 DAE) to prevent yield losses of 5%. This period to prevent yield losses of 2.5, 10 and 20% was 4- to 17-leaf stage (14-59 DAE), 6- to 12-leaf stage (25-47 DAE) and 8- to 9-leaf stage (31-36 DAE) respectively. The height and leaf area index of corn were significantly decreased by weed competition in both weed free and weed infested treatments ($P<0.01$). Results also showed that there was a significant positive correlation between yield and LAI of corn at silk stage when competing with weeds ($r= 0.97$).

***Keywords*—**Corn, Critical period, Gompertz, Logistic, Weed control.

I. Introduction

INTEGRATED weed management (IWM) involves a combination of cultural, mechanical, biological, genetic, and chemical methods for effective and economical weed control [17]. The principles of IWM should provide the foundation for developing optimum weed control systems and efficient use of herbicides. The critical period for weed control (CPWC) is a key component of an IWM program. It is a period in the crop growth cycle during which weeds must be controlled to prevent yield losses. The CPWC is useful for making decisions on the need for and timing of weed control. Timing of weed control measures is important to maintain optimum crop yield. Determining the CPWC could help reduce yield losses due to weed interference [10].

Controlling weeds based on CPWC is the most appropriate way to optimize weed control applications. With the aid of CPWC it is possible to make decisions on the need for and timing of weed control, and to control weeds only when efficient weed control is required. The CPWC could be used also to enhance the efficiency of other methods of weed management, including cultivation and flaming. Also reducing the number of herbicide treatments as a result of better timing and efficiency may reduce potential environmental contamination and the selection pressure for herbicide-resistant weeds [7].

The CPWC is the time period in the crop growth cycle during which weeds must be controlled to prevent unacceptable yield loss [4]. It has been defined as the time interval between the maximum weed-infested period, or the length of time that weeds which emerge with the crop can remain uncontrolled before they begin to compete with the crop and cause yield loss, and the minimum weed-free period, or the length of time that the crop must be free of weeds after emergence [12]. Thus, it is the minimum period of time during which the crop must be free of weeds to prevent crop yield loss. Knezevic et al.[10] described CPWC as a "window" in the crop growth cycle during which weeds must be controlled to prevent unacceptable yield losses.

The length of the CPWC may vary depending on the acceptable yield loss [7]. This concept is closely related to the use of weed thresholds, defined by Dawson [2] as the length of time that a crop can tolerate weed competition before yield loss exceeds the cost of control. The CPWC is determined by calculating the time interval between two components of weed interference. These are (1) the critical weed interference period or the maximum length of time during which weeds emerging soon after crop planting can coexist with the crop without causing unacceptable yield loss, and (2) the critical weed-free period or the minimum length of time required for the crop to be maintained weed-free before yield loss caused by late emerging weeds is no longer a concern [4, 7]

Corn (*Zea mays* L.) is an important crop for Iran, where it is often grown for human and animal consumption. Weeds are one of the most important factors in corn production in Iran. They cause important yield losses worldwide with an average of 12.8% despite weed control applications and 29.2% in the case of no weed control [8]. Therefore, weed control is an important management practice for corn production that should be carried out to ensure optimum grain and forage yield. Weed control in maize in Iran is carried out by mechanical and/or chemical methods. Weeds between plant rows are removed generally by mechanical cultivation, while weeds on the rows are controlled by hand hoeing or by herbicides. Although both methods are effective in controlling

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weeds, they increase production costs and have some disadvantages or side effects when applied intensively. To reduce the costs and risks of intensive weed control, the frequency or intensity of applications should be reduced or optimized.

Studies have been conducted around the world to determine the CPWC in corn, with a range of environmental conditions. Several investigators, reported a weed-free period of 50 days from seeding for corn in order to prevent yield loss in Mexico [13]; whereas, in the United States they reported a period of 3 to 6 weeks [9]. In the southeastern United States, the CPWC began 5 d after corn emergence and ended 53 d after corn emergence [14]. However, this method makes the comparisons among locations and years difficult because of different emergence dates and environments. In corn, leaf stages or accumulated thermal units could improve comparisons because the leaf appearance rate is highly dependent upon ambient temperatures [18]. In Ontario, Canada, Hall et al. [7] showed that the CPWC in corn began at the 3-leaf stage and ended at the 14-leaf stage. [5] determined CPWC for maize in Italy as the period between the 1- and 7-leaf stages in 1992 and between the 7- and 10-leaf stages in 1993. Del Pino and Covarelli [3] reported that a weed-free duration of 2 weeks starting 3 weeks after crop emergence is enough to provide acceptable grain yield. Another study, conducted in Turkey, showed that with 5% yield loss level, the CPWC was 5 wk, starting at 0.2 Weeks after emergence (WAE) and ending at 5.2 WAE, which corresponded to the one- to five-leaf stage of corn. In that research the CPWC increased to 8.9 wk, starting at 0 WAE and ending at 8.9 WAE, at the 2.5% yield loss level and at 10% yield loss level, the CPWC decreased to 1.7 wk, starting at 2.1 WAE and ending at 3.8 WAE. [8].

Results from later studies on the CPWC in a no-till system in Canada were quite different. In research by Halford et al. [6], it was concluded that the beginning of the CPWC was stable, usually beginning at the six-leaf stage, with the end of the CPWC being more variable, ranging from the nine- to 13-leaf stage. In the mid western United States, the beginning of the CPWC ranged from emergence to the seven-leaf stage of corn, with the end of the CPWC ranging from the five-leaf stage to anthesis [4]. A portion of the variability in the beginning and end of the CPWC in the study by Evans et al. [4] was due to differences in nitrogen fertilization. As nitrogen fertilization increased, there was a delay in initiation of the CPWC and generally a hastening to the end of the CPWC. Other reasons for variability in the initiation or end of the CPWC were differences in weed spectrum, density, and time of weed emergence among sites [4, 6, 7].

It can be concluded from the results of previous studies that the CPWC values are variable depending on the location or growing season. These differences can be attributed to variations in the composition of weed species, initial density or ground cover of weeds, as well as to climatic conditions, in which crop and weeds interfere [10]. Topography, climate, crop genetics, and cultural practices, such as tillage intensity, fertilization, seeding rate, and row width, are several factors that may influence the CPWC by directly affecting weed composition, weed density, time of weed emergence relative to the crop, or crop and weed growth. Thus, there is tremendous variability in the CPWC.

Many of the previous studies showed that weed species or crop management practices (e.g., nitrogen application rate, row spacing) affect the CPWC and results might not always apply to all regions [4, 11]. In addition, many of the weed species studied are not common in Iran. Results obtained from previous studies also showed variability in the CPWC even with similar weed species because of site-specific factors, such as planting pattern and environmental conditions [4, 11].

In order to provide more precise information for growers, CPWC should be determined specifically for a particular region by considering the weed composition and climatic conditions [10]. Therefore, this study aimed to estimate the optimum timing for weed control in corn and to determine the effect of the timing of weed removal and the duration of weed interference on corn yield under the growing conditions of southern Khorasan province in Iran, an area for which this type of information is lacking.

II. Materials and Methods

Field experiments were conducted in 2005 and 2006 at the Birjand University Experiment Station in the southern east of Iran. (32° 56′ North latitude, 59° 13′ East longitude, 1480 m). The soil type was clay loam with 0.6% organic matter and pH 8.2 in 2002. Soil preparation consisted of primary and secondary tillage as well as cultural practices was conducted according to local practices for corn production. Corn seeds, cultivar SC704, sown at a spacing of 20 cm within the row spaced 75 cm apart at a population density of 66,600 plants ha^{-1}. Sowing dates were 14 May 2005 and 20 May 2006. Plot size was five rows each 7 m long, and plots were separated by two border rows. The middle three rows of each plot were used for data collection. Fertilizers were applied at the rate of 112 kg P ha^{-1} at sowing and 205 kg N ha^{-1} with 50% applied at the time of sowing and 50% at the time of 7-8 leaf-stage of corn approximately 35 DAE. Water was applied by furrow irrigation to the plot area throughout the crop growing season. Amount of irrigation was adjusted to meet crop water needs based on precipitation and air temperature.

Experiments were conducted on the same site within the research station in successive years. Naturally occurring weed populations were used in trials. The experimental design was a randomized complete block (RCBD) with four replications. Two sets of treatments were imposed to represent both increasing duration of weed interference and the length of the weed-free period measured after planting. The first set of treatments established six levels of increasing duration of weed interference by delaying weed control from the time of crop emergence up to predetermined crop growth stages (weedy up to V_3, V_6, V_9, V_{12}, V_{15},and R_1) at which weed control was initiated and maintained for the remainder of the growing season. The second set of treatments established six levels of increasing length of the weed-free period by maintaining weed control from the time of crop planting up to the above-presented crop growth stages before subsequently emerging weeds were left uncontrolled for the remainder of the season. In addition, season long weedy and weed-free controls were included. Growth stages of the crop were determined from the number of visible leaf collars, as described by Ritchie et al. [15]. The progression of crop development was monitored for all weedy and weed-free controls by recording the average growth stage of 10 consecutive corn plants every 5 d. Weeds were removed by hand pulling and hoeing.

Two days before each weed removal, weeds were harvested from three 1-m^2 quadrats staggered on each side of the three middles corn rows within each experimental plot. Successive harvest areas were separated from one another by a minimum of 1 m of undisturbed vegetation. Harvests were excluded from a 1-m portion of both the front and rear of each experimental plot to minimize neighborhood effects. At each harvest weeds were clipped at the soil surface, sorted by species, counted, and dried at $70^{\circ C}$ to a constant moisture content to obtain a measure of aboveground dry weed biomass.

Final corn harvest dates were September 21, 2005 and September 27, 2006. Corn Leaf area index (LAI) and height were measured in all treatments at corn silk stage and prior to corn harvest respectively. Corn ears were hand-harvested from 4 m of three adjacent rows within each plot. Ears were threshed and subsequently dried at $70^{\circ C}$ to a constant moisture content. All yields are presented and analyzed on a dry weight basis to eliminate the error associated with adjusting moisture content.

Yield data of individual plots were calculated as the percentage of their corresponding weed-free plot yields. Relative yield data were subjected to analysis of variance with the use of the PROC MIXED function of Statistical Analysis System (SAS 1999), to assess the effect of the length of the weed-free period and increasing duration of weed interference on relative corn yields [4, 10, 14]. The statistical significance of treatment, year, and interaction between year and treatment combinations was evaluated at 5% level of probability. Nonlinear regression analyses with the PROC NLMIXED function of SAS were used to estimate the relative yield of corn as a function of increasing duration of weed interference or as a function of the length of the weed-free period, according to the procedure outlined by Knezevic et al. [10]. A three-parameter logistic equation, proposed by Hall et al. [7] and modified by Knezevic et al. [10] was used to describe the effect of increasing duration of weed interference on relative yield. The following logistic equation used was:

$$Y = \left[\left(\frac{1}{(\exp[A \times (T - B)]) + C}\right) + \left(\frac{C-1}{C}\right)\right] \times 100 \qquad (1)$$

Where Y is the relative yield (percent of season-long weed free yield), *T* is the duration of weed interference measured from the time of corn emergence in DAE, *B* is the point of inflection in DAE, and *A* and *C* are constants.

The Gompertz model has been shown to predict the relationship between relative yield, as influenced by the length of the weed-free period [7, 10]. The model has the following form.

$$Y = A \times \exp[-B \times \exp(-C \times T)] \qquad (2)$$

Where Y is the relative yield (percent of season-long weed-free yield), *A* is the yield asymptote or maximum yield in the absence of weed interference, *B* and *C* are constants, and *T* is the length of the weed-free period after corn emergence in DAE.

Goodness of fit was studied in terms of minimum mean square error (MSE) and maximum R^2. The logistic equation [1] was used to determine the beginning of the CPWC, and the Gompertz equation [2] was used to determine the end of the CPWC for acceptable yield loss levels of 2.5%, 5%, 10%, 15% and 20%.

III. Results and Discussion

The weed population was composed of 10 species in 2005, and 9 species in 2006 (Table 1). In both years, the most common weeds in the experiments were Common lambsquarters (*Chenopodium album* L.), Saltwort (*Salsola kali* L.), Heliotrope (*Heliotropium europaeum* L.) and Camel thorn (*Alhagi pseudalhagi* M.B. Desv.). These four species represented 76 and 80% of the total weed population in 2005 and 2006, respectively. Common lambsquarters and Saltwort were the most predominant species and accounted for 51 and 55% of the weed populations in 2005 and 2006, respectively.

Corn yield in the weed-free treatment was 8,210 kg ha^{-1} in 2005 and 6,090 kg ha^{-1} in 2006. There was no year by treatment interaction; therefore, relative yield data were combined over years. Parameters for logistic and Gompertz equations as well as the beginning and the end of the CPWC were estimated with the combined data for both years (Table 2). Corn yield response to increasing duration of weed-infested period or weed-free period was adequately described by the regression models with R^2 values of 0.95 and 0.97 respectively (Table 2).

The length of the CPWC in corn was 45, 36, 22, 13 and 5 days with 2.5, 5, 10, 15 and 20% acceptable yield loss levels (AYL), respectively. The onset of the CPWC was 19 DAE (fifth leaf stage of corn (CLS)) at 5% AYL and 14 DAE (4 CLS), 25 DAE (6 CLS), 28 DAE (7 CLS) and 31 DAE (8 CLS) at 2.5, 10, 15 and 20% AYL, respectively (Fig.1).

Table 1. The population density (plants/m^2) of weed species in the experimental area in weed-infested check at silk stage of corn

Weed species	Weed density 2005	Weed density 2006
Alhagi pseudalhagi (L.)	2.83	2.25
Amaranthus hybridus (L.)	0.67	–
Amarantus retroflexus (L.)	0.33	0.92
Cardaria draba (L.) Desv	0.75	–
Chenopodium album (L.)	7.25	6.17
Convolvulus arvensis (L.)	1.42	0.92
Datura stramonium (L.)	–	0.33
Heliotropium europaeum (L.)	3.17	1.83
Hyoscyamus pusillus (L.)	1.75	–
Kochia scoparia (L.) Schral.	0.58	–
Salsola kali (L.)	4.50	3.17
Solanum nigrum (L.)	–	0.75
Tribulus terrestris (L.)	–	0.50
Total	23.25	16.84

Weed control should therefore start 2 weeks after crop emergence to avoid a yield loss of more than 2.5%. The CPWC for AYL of 2.5, 5, 10, 15 and 20% ended at 59 DAE (17 CLS), 55 DAE (15 CLS), 47 DAE (12 CLS), 41 DAE (11 CLS) and 36 DAE (9 CLS) (Table 3 and Fig.1).

Changes in corn height in response to weed interference were similar to changes in yield. As the duration of weed-infested period increased from V_E to R_1, corn height decreased from 175 to 126 cm. Conversely, as the duration of weed-free period increased from V_E to R_1, corn height increased from 117 to 165 cm (data not shown).

Table 2. Parameter estimates with standard errors of the three-parameter logistic model used to determine the critical timing of weed removal and the Gompertz model used to determine the critical weed-free period for corn in 2005 and 2006. The models were fitted to relative yields of corn (expressed as a percentage of the weed-free control) as a function of increasing duration of weed interference and increasing length of weed-free period respectively (in DAE). Refer to text (Equations 1 and 2) for models description.

Logistic model		Gompertz model	
Parameters	Value (SE)	Parameters	Value (SE)
A	0.15 (0.04)	*A*	106.30 (5.39)
B	35.38 (2.60)	*B*	1.89 (0.27)
C	1.35 (0.10)	*C*	0.05 (0.01)
R^2= 0.95		R^2= 0.97	

LAI of corn was significantly affected by weed interference. Although the corn LAI was not decreased with weed infested durations less than 25 DAE (V_6), it was significantly decreased up to 43, 39, 77, 72 and 79% when weeds infested to V_9, V_{12}, V_{15}, R_1 and silk stages of corn respectively (data not shown). There was a significant positive correlation (P<0.01) between corn LAI at silk stage and its yield (r= 0.97) (Fig.2). Knezevic et al. 2003 showed that the LAI of corn at silk stage could be described corn yield losses caused by weeds interferences.

Table 3. The critical period of weed control (CPWC) for corn calculated from Logistic and Gompertz equations at five acceptable yield loss levels (AYL) expressed as days after emergence (DAE) and corn leaf stages (CLS).

ALY	Beginning of CPWC		End of CPWC	
	DAE	CLS	DAE	CLS
2.5%	14	4	59	17
5%	19	5	55	15
10%	25	6	47	12
15%	28	7	41	11
20%	31	8	36	9

Weeds reduced corn yield by approximately 77% when allowed to compete with the crop from planting through harvest. The CPWC determined in our research for the southern east region of Iran is generally similar to that determined by Evans et al. [4], shorter duration in comparison to that determined by Norsworthy and Oliverira [14] and longer duration in comparison to that determined by Isik et al. [8]. This variation could be explained by differences in environmental conditions and weed species diversity among research sites. Norsworthy and Oliveira [14] found large differences in the CPWC in corn in studies conducted at two sites with different weed populations in the southeastern United States. Our results suggest that weed control measures in southern east of Iran can be delayed up to about 20 days after corn emergence. Previous study has reported similar results in northern east region of Iran [1]. Several researchers have indicated that the end of CPWC was not stable but was highly dependent on the density, competitiveness, and emergence periodicity of the weed population ([4, 6, 14].

The degree of interference between corn and weeds is determined in part by limiting resources like water, nutrients, and light. Corn size and final yield is therefore the result of its ability to capture available resources throughout the growing season.

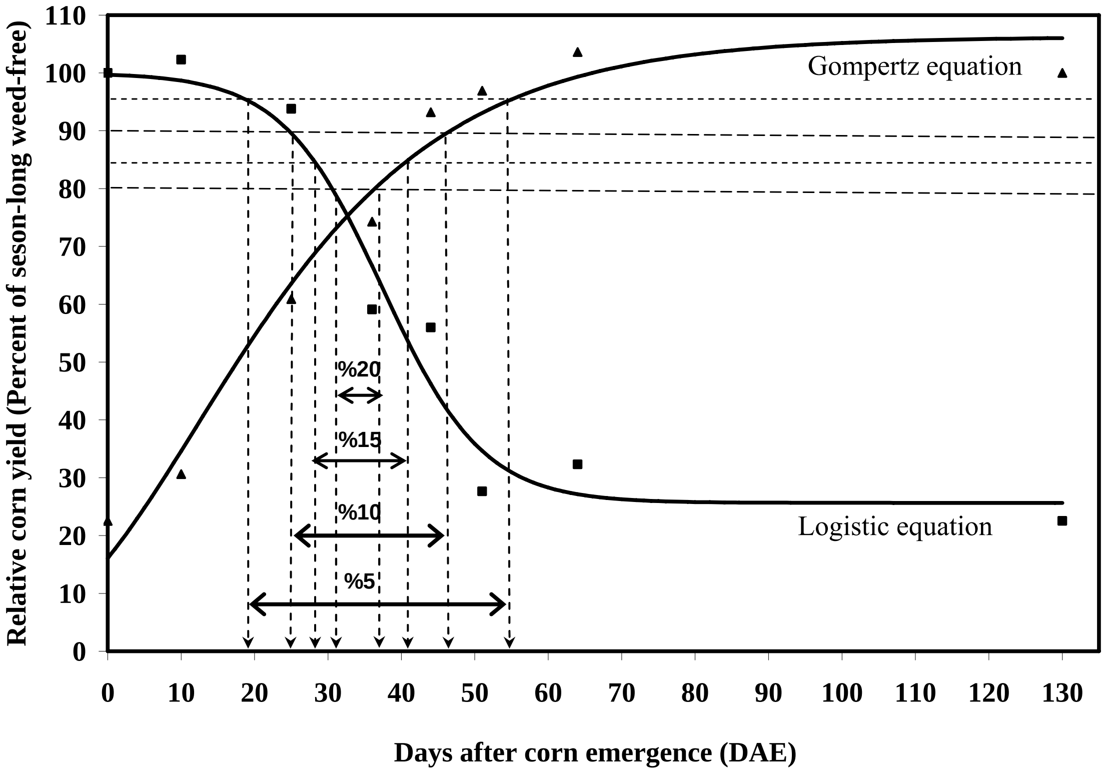

Fig 1. Effect of weed interference on total yield of corn. Increasing duration of weed interference (■) and fitted curves as calculated by the logistic equation; increasing weed-free period (▲) and fitted curves as calculated by the Gompertz equation. Dots represent observed data averaged over 2005 and 2006. Horizontal dashed lines indicate the 5%, 10%, 15% and 20% acceptable yield loss levels used to determine the CPWC, whereas vertical dashed lines indicate the beginning and end of CPWC. Parameters for fitted curves given in Table 2.

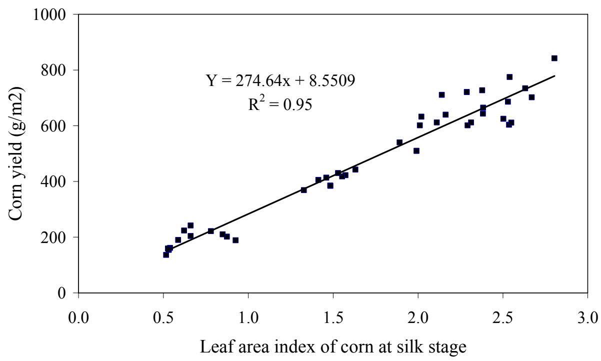

Fig. 2. Relationship between corn yield and its leaf area index at silk stage in different weed-interference and weed-free treatments as obtained using linear regression model, y= 8.55 + 274.64 x, R^2= 0.95 Dots represent observed data averaged over 2005 and 2006.

Weeds should have limited effects on corn yield and height if they are controlled in a timely manner. Based on 5% acceptable yield loss, results of this research suggest that under our experimental conditions corn tolerates weed interference until 19 DAE or 5 CLS, suggesting that control measures should start at that stage. The crop should be kept weed free until 55 DAE or 15 CLS in order to prevent yield loss in excess of 5%. Weeds that emerge after that, grow in a competitive disadvantage in comparison with corn.

In Iran, hand weeding and herbicide applications are the major methods of weed control in corn. According to the results of the CPWC, growers could improve timing of post emergence herbicide applications and hand weeding. Further studies should be conducted to determine the CPWC in other areas where weed populations are different from those reported here.

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