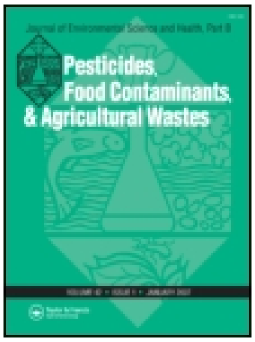

Taylor & Francis
Taylor & Francis Group

Journal of Environmental Science and Health, Part B
Pesticides, Food Contaminants, and Agricultural Wastes

ISSN: 0360-1234 (Print) 1532-4109 (Online) Journal homepage: http://www.tandfonline.com/loi/lesb20

Using Thermal Units for Estimating Critical Period of Weed Competition in Off-Season Maize Crop

Ramiro Fernando López-Ovejero , Axel Garcia y Garcia , Saul Jorge P. de Carvalho , Pedro J. Christoffoleti , Durval Dourado Neto , Fernando Martins & Marcelo Nicolai

Journal of Environmental Science and Health, B40:1–11, 2005

ISSN: 0360-1234 (Print); 1532-4109 (Online)
DOI: 10.1081/PFC-200034196

Taylor & Francis
Taylor & Francis Group

Using Thermal Units for Estimating Critical Period of Weed Competition in Off-Season Maize Crop

Ramiro Fernando López-Ovejero,[1,*] Axel Garcia y Garcia,[2] Saul Jorge P. de Carvalho,[1] Pedro J. Christoffoleti,[1] Durval Dourado Neto,[1] Fernando Martins,[1] and Marcelo Nicolai[1]

[1]Department of Crop Science, University of São Paulo, Piracicaba, São Paulo, Brazil
[2]Department of Biological and Agricultural Engineering, The University of Georgia, Griffin, Georgia, USA

Brazilian off-season maize production is characterized by low yield due to several factors, such as climate variability and inadequate management practices, specifically weed management. Thus, the goal of this study was to determinate the critical period of weed competition in off-season maize (*Zea mays* L.) crop using thermal units or growing degree days (GDD) approach to characterize crop growth and development. The study was carried out in experimental area of the University of São Paulo, Brazil, with weed control (C), as well as seven coexistence periods, 2, 4, 6, 8, and 12 leaves, flowering, and all crop cycle; fourteen treatments were done. Climate data were obtained from a weather station located close to the experimental area. To determine the critical period for weed control (CPWC) logistic models were fitted to yield data obtained in both W and C, as a function of GDD. For an arbitrary maximum yield loss fixed in 2.5%, the CPWC was found between 301 and 484 GDD (7–8 leaves). Also, when the arbitrary loss yield was fixed in 5 and 10%, the period before interference (PBI) was higher than the critical weed-free period (CWFP), suggesting that the weeds control can be done with only one application, between 144 and 410 GDD and 131 and 444 GDD (3–8 leaves), respectively. The GDD approach to characterize crop growth and development was successfully used to determine the critical period of weeds control in maize sown off-season. Further works will be necessary to better characterize the interaction and complexity of maize sown off-season with weeds. However, these results are encouraging because the possibility of the results to be extrapolated and because the potential of the method on providing important results to researchers, specifically crop modelers.

*Correspondence: Ramiro Fernando López-Ovejero, Department of Crop Science, University of São Paulo—ESALQ/USP, Av. Pádua Dias, 11. C.P. 09, Piracicaba, SP 13419-900, Brazil; E-mail: rfloveje@esalq.usp.br.

Key Words: Corn; Interference; Critical period; Growing degree days; Off-season.

INTRODUCTION

Maize (*Zea mays* L.) is one of the most important cereals in the world and produced widely in Brazil, not only during normal season but most recently as an alternative crop for off-season period (Autumn–Winter, called "Safrinha" in Portuguese), since the area has increased in the last years[1] in a rate of 150,000–160,000 ha per year, from 2.2 million ha in 1996 to 3.3 million ha in 2003.[2] It is a high-risk crop, mainly due to varying climatic conditions,[3] as well as inadequate management practices, specifically weed control; that results in low yields. Weeds interference can occur directly, by competition and allelopathy, or indirectly, by hosting pests and diseases.[4] Thus, water, light, nutrients, and space are resources that will be also used by weeds.[5]

Weed interference level varies and depends on factors related to the crop (variety, row spacing), infesting community (specific community, density, and distribution); environment (weather conditions, crop management), and weed and crop moment, and coexistence duration.[5]

Interference level can be defined as a reduction of crop production due to weeds, when compared with the production of a crop that was growth and developed without weeds along all the plant cycle. The period before weed interference is called PBI, critical weed-free period is called CWFP, and the interval between PBI and CWFP is called critical period for weed control (CPWC), on which the crop has to be without weed competition.[6]

Several studies have determined weed interference periods for maize crop. However, most of them have used days after emergence (DAE) as a explanatory variable for PBI, CWFP, or CPWC.[7,8] Meanwhile, it is evident that plant cycles are extremely affected by climate variability, such as relative humidity, air and soil temperature, rainfall, solar radiation, and photoperiod, that can provoke inconsistencies on the results based on DAE. Another option for defining weed interference periods for maize is using the phenological scale, as demonstrated by Kozlowski.[9] Thus, maize phenological stages can be expressed on the basis of thermal units.[10,11]

Growing degree days is a useful quantitative variable that measures the time required for plant growth and development.[12] Also, GDD approach is easier than a discrete variable, such as crop growth stages, for using in regression models because it provides a continuous and precise scale for the independent variable, and because can be used for comparing data from different locations, years, and sowing dates.[13]

The goal of this study was to determine the critical period to prevent weeds interference on maize sown off-season through the use of thermal units.

MATERIALS AND METHODS

The study was carried out in experimental area of the Department of Crop Science, University of São Paulo, Brazil; located at 22° 42′ 30″ latitude S and 47° 38′ 00″ longitude W, and 546 m above sea level. The area has been historically cultivated under conventional system. To avoid water stress, the experiment was irrigated when necessary using a center pivot system. Climate of the region is Cwa with a rainy summer and dry winter.[14] Soil of the experimental area is classified as a Typic Eutrodox.[15]

The experiment was sown in March 22nd, 2002, using a commercial short season hybrid "Valent," with harvest in August 30th, 2002. Fertilizers were applied at 380 kg ha^{-1} of the formula 08-28-16. Nitrogen was split in one application at sowing and two applications in side dress.

The experimental design was randomized blocks with three replications. From the combination of two interference models; initially without weed control (W) and initially with weed control (C), as well as seven coexistence periods, 2, 4, 6, 8, and 12 leaves, flowering, and all the cycle; fourteen treatments were done (Table 1). Each plot consisted in 4 rows, spaced 0.90 m, with 4.0 m of length, totalizing 14.4 m^2 for each plot, being the two central rows considered the useful area. At the end of each initial period without control (W), two sampling dates for weed population were done in an area of 0.25 m^2. Thereafter, weed removal in the plots was done manually. Collected weeds were counted, identified,[4] and weighted. The C interference models were manually maintained without weeds until to reach the given phenological stage. At harvest, two weed samples were taken in 0.25 m^2 following the same procedure used for W samples.

At flowering, two plants were collected for maximum leaf area index (LAI). Also, for LAI temporal analysis, destructive sampling was done and LAI was estimated as a function of width and length of individual leaves using the McKee proposal[16]:

$$A = \sum_{i=1}^{I} 0.75 L_i W_i (i = 1, 2, 3, \ldots, i-1, I \text{ leaves}) \quad (1)$$

Table 1: Treatments characterization for the models: initially without control (W) and initially with control (C).

	Interference model	
Treatments	**Initially without weed control (W)**	**Initially with control (C)**
1	0–2 leaves	0–2 leaves
2	0–4 leaves	0–4 leaves
3	0–6 leaves	0–6 leaves
4	0–8 leaves	0–8 leaves
5	0–12 leaves	0–12 leaves
6	0–Flowering	0–Flowering
7	Complete cycle	Complete cycle

where A corresponds to leaf area (cm^2), L_i is the maximum leaf length, W_i is the maximum leaf width, and 0.75 is the empirical parameter of adjustment.

Climate data were obtained from a weather station located close to the experimental area. The GDD was estimated as proposed by Gilmore and Rogers[12]:

$$\mathrm{GD} = \sum_{j=1}^{J}\left[\frac{(T_{\max_j} + T_{min_j})}{2} - T_b\right](j = 1, 2, 3, \ldots, j-1, J\,\text{days}) \tag{2}$$

where $T_{\max}$ corresponds to maximum air temperature (if $T_{\max} > 30°C$, then $T_{\max} = 30°C$) $T_{\min}$ corresponds to minimum air temperature (if $T_{\min} < 10°C$, then $T_{\min} = 10°C$, T_b is the maize base temperature (10°C) assumed[17,18] and largely used in several studies for Brazilian conditions, such as Gadioli et al.[19] For yield purposes, harvest was done in the central rows of each plot, totalizing 20 plants per row. The kernels were corrected to 14% humidity content and then rescaled to kg ha^{-1}.

A four parameters logistic model was fitted to yield and leaf area as a function of the GDD, as well as to determinate weed critical periods.[20,21] Thus, the Table Curve 2D®,[22] specific software for equations, was performed for solving the following model:

$$y = a + \frac{b}{[1 + (x/c)^d]} \tag{3}$$

where y is yield (kg ha^{-1}) or leaf area (cm^2), x stands for GDD values, and a, b, c, and d are empirical coefficients. The coefficient a correspond to minimum yield or leaf area, b is the difference between maximum and minimum yield or leaf area, c is the GDD value that give 50% decrease in the maximum yield or leaf area, and d correspond to slope.[23]

From 2.5, 5, and 10% arbitrary losses of the maximum yield obtained in each C treatment plot during all crop cycle, values were obtained and used in the W and C models allowed to determine the GDD for PBI and CWFP. The simple difference between CWFP and PBI was the CPWC value.

RESULTS AND DISCUSSION

No extreme mean air temperature values were observed during the experimental season. However, maximum temperature varies from almost 35 to 19°C and minimum temperature varies from almost 20°C to close to 6°C during a short period in July. Despite enough total amount of rainfall during the crop cycle (362 mm), irrigation was necessary to avoid water stress, mainly from mid-May to end-July (Fig. 1).

A total of 24 different weed plant species were identified in the experimental area, being 71% dicotyledonous. Due to the number of species (five), the most

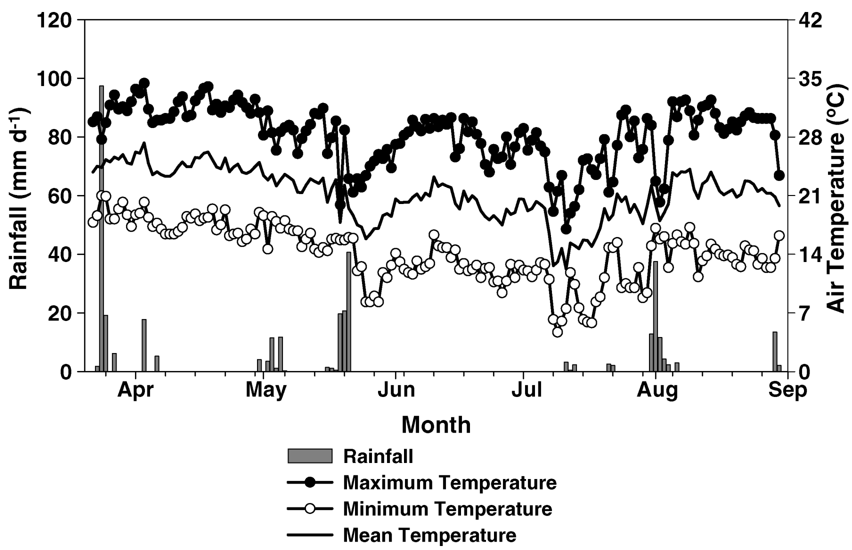

Figure 1: Weather characterization during the period that the experiment was carried out.

important dicotyledonous family founded was Asteraceae, followed by Amaranthaceae and Euphorbiaceae, with two species each one; species normally found during that season. The most important monocotyledon family founded was Poaceae with five species. A complete list of weeds identified is presented in Table 2.[24]

Total weed biomass temporal variation observed was as higher as 125 g m^{-2} for the model C and as higher as 225 g m^{-2} for the model W. Also, weeds density for C was around 50 plants m^{-2}, while for W we found up to 230 plants m^{-2} (Figs. 2 and 3).

The cumulative GDD obtained were 741 at flowering and 1710 at harvest (Table 3), values in agreement with those that characterize a maize short season hybrid.[25]

Logistic equation fitted to yield and leaf area for W and C interference models was adequate. For yield variable, except the empirical parameter d; a, b, and *c* parameters were significantly different from zero for W and C data, with 0.95 and 0.91 r^2, respectively (Table 4). For the W interference model was observed a decrease in yield when no weeds control was done until 300 GDD or after; while the opposite was observed for the C interference model. Thus, control should be made before to reach 300 GDD (Fig. 4).

Some inconsistencies were observed when the equation was fitted to LAI values, specifically for the C interference model. However, coefficients of determination were satisfactory. Empirical parameters obtained for the logistic equation fitted to W and C yield and LAI are presented in Table 4. We observed that LAI was affected by weed interference from 365 to 587 GDD (8–12 leaves).

Table 2: Weed species observed in the experiment (from March to August 2002).

Family	Specie	International code
Monocotyledonous		
Commelinaceae	*Commelina benghalenisis* L.	COMBE
Cyperaceae	*Cyperus rotundus* L.	CYPRO
	Brachiaria plantaginea (Link) Hitchc.	BRAPL
	Cenchrus echinatus L.	CCHEC
Poaceae	*Digitaria horizontalis* Willd.	DIGHO
	Echinochloa crusgalli (L.) P. Beauv.	ECHCG
	Eleusine indica (L.) Gaertn.	ELEIN
Dicotyledonous		
Amaranthaceae	*Alternanthara tenella* Colla	ALRTE
	Amaranthus viridis L.	AMAVI
	Acanthospermum hispidum DC.	ACNHI
	Bidens pilosa L.	BIDPI
Asteraceae	*Emilia sonchifolia* (L.) DC.	EMISO
	Ageratum conyzoides L.	EUPPF
	Parthenium hysterophorus L.	PTNHY
Brassicaceae	*Coronopus didymus* (L.) Sm.	COPDI
Convolvulaceae	*Ipomoea grandifolia* (Dammeer) O'Donell	IAOGR
Euphorbiaceae	*Chamaesyce hirta* (L.) Millsp.	EPHHI
	Phyllanthus tenellus Roxb.	PYLTE
Fabaceae	*Indigofera hirsuta* L.	INDHI
Lamiaceae	*Leucas martinicensis* (Jacq.) W.T.	LEVMA
Malvaceae	*Sida santaremnensis* H. Monteiro	SIDSN
Portulacaceae	*Portulaca oleraceae* L.	POROL
Rubiacea	*Richardia brasiliensis* Gomes	RCHBR
Solanaceae	*Solanum americanum* Mill.	SOLAM

Based on Salgado et al.[25]

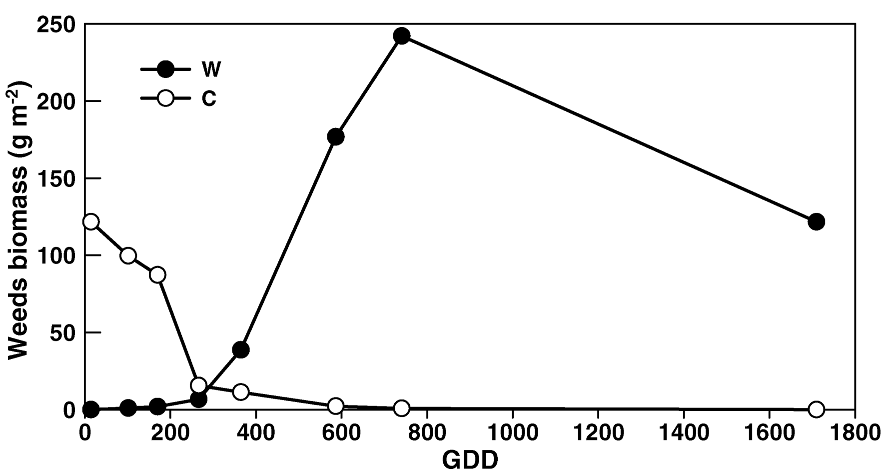

Figure 2: Temporal variation of total weed biomass for W and C, as a function of GDD.

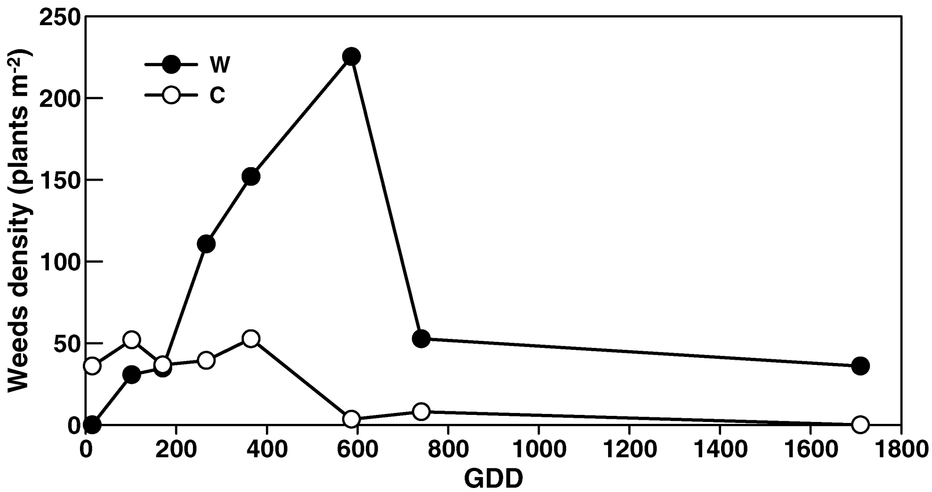

Figure 3: Temporal variation of total weed density, as a function of GDD.

For the W interference model, it seems that coexistence until 8 to 12 leaves do not affected the temporal variation of LAI, similar results were obtained for the C interference model when control was made until 8 leaves (Figs. 5 and 6). These results are in agreement with those obtained when an arbitrary 2.5% yield loss was assumed. Because LAI allows estimating plant developmental stage as well as its potential for intercepting energy,[26] reductions in LAI will result in a decrease in plant metabolism and consequently, carbohydrates losses. Thus, the less photo assimilates drained to the cob, the less cumulative reserves to be drained to kernel.[25]

As a practical consequence, a control when the crop is at the 8 leaves stage should resolve the problem. However, we have to emphasize that maize weed control from 7 to 8 leaves will be difficult if performed by conventional methods, until 5 unfolded leaves.

Applying arbitrary losses of 2.5, 5.0, and 10.0% to maximum yield obtained in C with control during all the cycle (5502 kg ha^{-1}), acceptable limits of 5364,

Table 3: Crop cycle characterization as a function of days after emergence (DAE), phenological stages, and cumulative growing degree days (GDD).

Date	DAE	Phenological stage	Cumulative GDD
March 28	0	Emergence	15
April 03	6	2 leaves	102
April 08	11	4 leaves	170
April 15	18	6 leaves	266
April 22	25	8 leaves	365
May 09	42	12 leaves	587
May 23	56	Flowering	741
August 30	155	Harvest	1710

Table 4: Empirical parameters obtained for the logistic model when fitted to W and C yield and leaf area data.

Variable	*a*	*b*	*c*	*d*	r^2
Model initially without control (W)					
Yield (kg ha^{-1})	432.7[a]	1090.4[a]	464.1[a]	6.9	0.95
Leaf area (cm^2)	4619.3[a]	1380.5[a]	743.9[a]	8.4	0.80
Model initially with control (C)					
Yield (kg ha^{-1})	4463.5[a]	874.1[a]	127.8[a]	−7.4	0.91
Leaf area (cm^2)	4560.0[a]	1402.0[a]	147.7	−1.2	0.81

[a]Significantly different from zero based on a *t* test for $p < 0.05$.

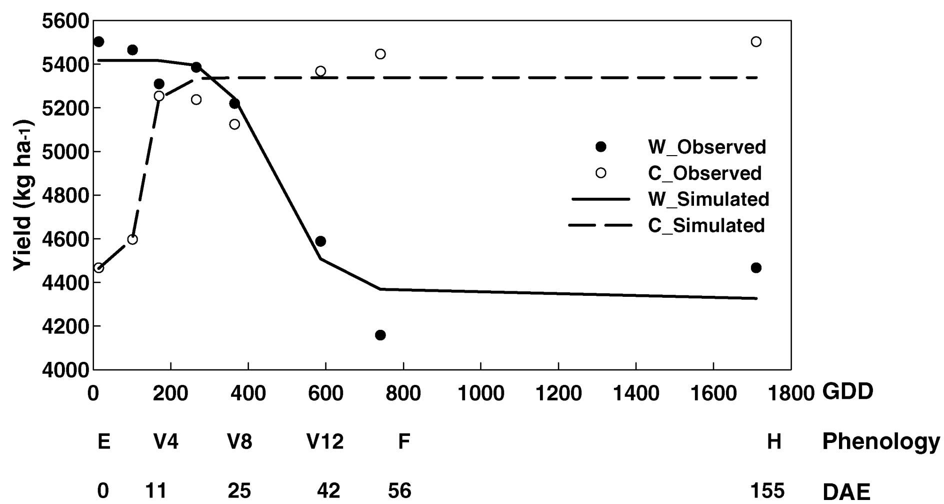

Figure 4: Maize yield as a function of the coexistence model and GDD, or phenology, or DAE: without weed control (W) and with control (C).

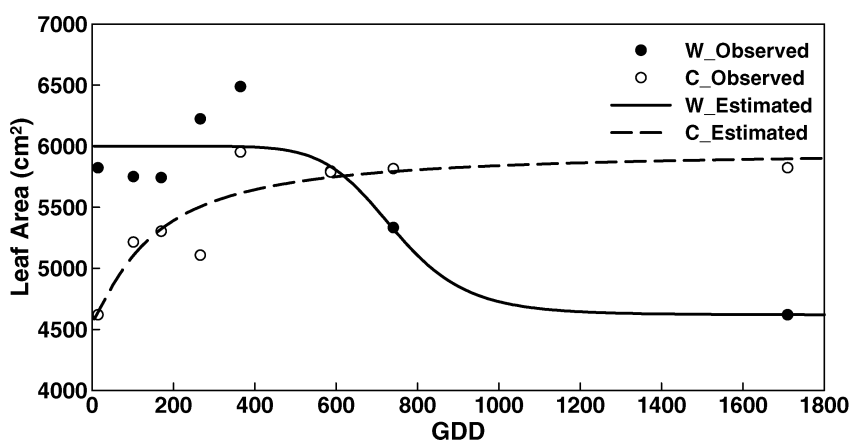

Figure 5: Temporal variation of maize leaf area for W and C interference models, as a function of GDD.

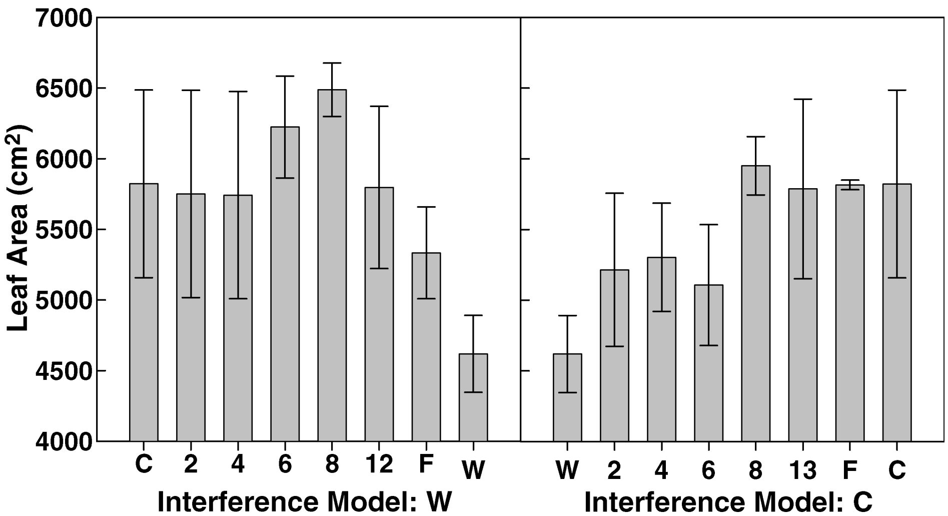

Figure 6: Maize leaf area as a function of the coexistence model: without weed control (W) and with control (C). For W model, control was realized until 2, 4, 6, 8, and 12 leaves, flowering (F), and W. For C model, control was realized from 2, 4, 6, 8, and 12 leaves, flowering, and C.

5089, and 4951 kg ha^{-1} were found, respectively. These limits were used in the logistic model to obtain PBI and CWFP values (Table 5). For maize off-season and assuming an arbitrary yield loss of 2.5%, we obtained values of CPWC between 301.55 and 484.8 GDD (7 to 8 leaves). These results are in agreement with those reported for maize in normal season by Bedmar et al.[27] When maize presents four to six unfolded leaves, apical meristem ends differentiation and panicle primordial begins to differentiate, moment on which is defined the number of leaves and consequently, the potential LAI. Thereafter, at seven to nine unfolded leaves, it begins the flowering differentiation, which will produce the ear, followed by the number of rows per ear, and the number of kernels per row between 12 leaves to anthesis.[26] Thus, weed interference affected the critical period of the plant, on which the potential of production is defined.

For yield losses between 5 to 10%, PBI was higher than CWFP, suggesting that the control can be done in only one application in the period between

Table 5: Critical period before the interference (PBI) and total period to prevent the interference (CWFP) for 2.5, 5, and 10% of arbitrary losses, as a function of growing degree days (GDD), phenology, and days after emergence (DAE).

	GDD		Phenology		DAE	
Losses (%)	**PBI**	**CWFP**	**PBI**	**CWFP**	**PBI**	**CWFP**
2.5	302	485	7 leaves	8 leaves	21	34
5	411	146	8 leaves	3 leaves	29	10
10	445	132	8 leaves	3 leaves	32	09

145 and 411 GDD and between 132 and 445 GDD, respectively. Similar situations were obtained by Kuva et al.[28] and Spadotto et al.[29] for sugar cane and soybean, respectively.

The GDD approach to characterize crop growth and development was successfully used to determine the critical period of weeds control in maize sown off-season. It is noteworthy that further works will be necessary to better characterize the interaction and complexity of maize sown off-season with weeds. However, these results are encouraging because of the possibility to be extrapolated and owing to the potential of the method in providing important results to researchers, specifically crop modelers.

REFERENCES

1. Tsunechiro, A. Milho: prognostico agrícola. APTA São Paulo **2002**, *2*, 233–240.

2. FNP Consultoria and Comércio. *Agrianual: Anuário da Agricultura Brasileira*; FNP Consultoria and Comércio: São Paulo, Brazil, **2004**; 496 pp.

3. Soler, C.M.T.; Hoogenboom, G.; Sentelhas, P.C.; Duarte, A.P. Predicting Yield Variability of Maize for the State of Sao Paulo, Brazil with the CERES-Maize model, Annual Meetings Abstracts [CD-ROM], ASA, CSSA, and SSSA: Madison, WI, 2003.

4. Lorenzi, H. *Manual de Identificação e Controle de Plantas Daninhas: Plantio Direto e Convencional*, 5th Ed.; Instituto Plantarum: Nova Odessa, Brasil, 2000; 339 pp.

5. Bleasdale, J.K.A. Studies on plant competition. In *The Biology of Weeds*; Harper, J.L., Ed.; Blackwell Scientific Publication: Oxford, 1960; 133–142.

6. Pitelli, R.A.; Durigan, J.C. Terminologia para períodos de controle e convivência de plantas daninhas em culturas anuais e bianuais. In *Resumos*, 15th Congresso Brasileiro de Herbicidas e Plantas Daninhas, Belo Horizonte, 1984; SBHED: Piracicaba, São Paulo, Brazil, 1984; 37 pp.

7. Beckett, T.H.; Stoller, E.W.; Wax, L.M. Interference of four annual weeds in corn (*Zea mays*). Weed Sci. **1988**, *36* (4), 764–769.

8. Hall, M.R.; Swanton, C.J.; Anderson, G.W. The critical period of weed control in grain corn (*Zea mays*). Weed Sci. **1992**, *40* (3), 441–447.

9. Kozlowski, L.A. Período crítico de interferência das plantas daninhas na cultura do milho baseado na fenologia da cultura. Planta Daninha **2002**, *20* (3), 365–372.

10. Kinery, J.R. Maize phase development. In *Modeling Plant and Soil Systems*; Hanks, J., Ritchie, J.L., Eds.; Agronomy Monograph No. 31; ASA: Madison, WI, 1991; 55–69.

11. McMaster, G.S.; Wilhelm, W.W. Growing degree-days: one equation, two interpretations. Agric. For. Meteorol. **1997**, *87*, 291–300.

12. Gilmore, E.C.; Rogers, R.S. Heat units as a method of measuring maturity in corn. Agron. J. **1958**, *50*, 611–615.

13. Knezevic, S.Z.; Evans, S.P.; Mainz, M. Row spacing influences the critical timing for weed removal in soybean (*Glycine max*). Weed Technol. **2003**, *17*, 666–673.

14. Köppen, W. *Climatologia: com un Estudio de los Climas de la Tierra*; Fondo de Cultura Económica: Mexico, 1948; 478 pp.

15. United State Department of Agriculture. *Keys to Soil Taxonomy*, 9th Ed.; National Resources Conservation Service: US, 2003; 332 pp.

16. McKee, G.W.A. Coefficient for computing leaf area in hybrid corn. Agron. J. **1964**, *56*, 240–241.

17. Cross, H.Z.; Zuber, M.S. Prediction of flowering dates in maize based on different methods of estimating thermal units. Agron. J. **1972**, *64*, 351–355.

18. Barbano, T.M.; Duarte, P.A.; Brunini, O.; Reco, P.C.; Paterniani, M.E.A.G.; Kanthackl, R.A.D. Base-temperature and accumulated heat units for the sub-period sowing-flowering phase for maize cultivars in São Paulo State. Rev. Bras. de Agrometeorol. **2001**, *9*, 261–268.

19. Gadioli, J.L.; Dourado-Neto, D.; Garcia y Garcia, A.; Basanta, M.D.V. Temperatura do ar, rendimento de grãos de milho e caracterização fenológica associada à soma calórica. Sci. Agric. **2000**, *57* (3), 377–383.

20. Cousens, R. Misinterpretations of results in weed research through inappropriate use of statistics. Weed Res. **1988**, *28*, 281–289.

21. Cousens, R. Aspects of the design and interpretation of competition (interference) experiments. Weed Technol. **1991**, *5*, 664–673.

22. Systat Software Inc. *TableCurve 2D® Software*; Point Richmond: CA, US, 2002.

23. Seefeldt, S.S.; Jensen, S.E.; Fuerst, E.P. Log-logistic analysis of herbicide dose-response relationship. Weed Technol. **1995**, *9*, 218–227.

24. Salgado, T.P.; Alves, P.L.C.A.; Mattos, E.D.; Martins, J.F.; Hernandez, D.D. Períodos de interferência das plantas daninhas na cultura do algodoeiro (*Gossypium hirsutum*). Planta Daninha **2002**, *20* (3), 373–379.

25. Fancelli, A.L.; Dourado-Neto, D. Milho: ecofisiologia e rendimento. In *Tecnologia da Produção de Milho*, 1st Ed.; Fancelli, A.L., Dourado-Neto, D., Eds.; Publique: Piracicaba, São Paulo, Brazil, 1997; 157–170.

26. Andrade, F.; Cirilo, A.; Uhart, S.; Otegui, M. *Ecofisiologia Del Cultivo de Maíz*, 1st Ed.; La Barrosa: Balcarce, Buenos Aires, 1996; 15–117.

27. Bedmar, F.; Manetti, P.; Monterubbianesi, G. Determination of the critical period of weed control in corn using a thermal basis. Pesqui. Agropecu. Bras. **1999**, *34* (2), 187–193.

28. Kuva, M.A.; Pitelli, R.A.; Christoffoleti, P.J.; Alves, P.L.C.A. Períodos de interferê-ncia das plantas daninhas na cultura da cana-de-açúcar. I—Tiririca. Planta Daninha **2000**, *18* (2), 241–251.

29. Spadotto, C.A.; Marcondes, D.A.S.; Luiz, A.J.B.; Silva, C.A.R.da. Determinação do período crítico para prevenção da interferência de plantas daninhas na cultura da saja: uso do modelo "broken-stick." Planta Daninha **1994**, *12* (2), 59–62.