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Phosphorus Application Influences the Critical Period of Weed Control in Lettuce

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Field studies were conducted in 2010 and 2011 at Belle Glade, FL, to evaluate the influence of phosphorus (P) applications (98, 196, and 293 kg P ha^{-1}) on the critical period of weed control (CPWC) in lettuce. Natural populations of mixed weed species were allowed to interfere with lettuce in a series of treatments of both increasing duration of weed interference and the duration of weed-free period imposed within 98, 196, and 293 kg P ha^{-1} levels added to the soil. The beginning and end of the CPWC for each P fertilization level based on a 5% acceptable marketable fresh lettuce yield loss level was determined by fitting log-logistic and Gompertz models to represent the increasing duration of weed interference and the duration of weed-free period, respectively. The CPWC in lettuce was estimated to be 4.6, 3.4, and 2.3 wk at 98, 196, and 293 kg P ha^{-1}, respectively. The beginning of the CPWC was delayed at the highest P fertilization level (293 kg P ha^{-1}), whereas the end of the CPWC was hastened at the same P fertilization level. Our study shows that inadequate levels of P fertilization in lettuce result in the need for more-intensive weed management practices to attain acceptable yields.

Nomenclature: Lettuce, *Lactuca sativa* L.

Key words: Duration of interference, duration of weed-free period, critical timing of weed removal, critical weed-free period, weed competition, yield loss.

Lettuce is an important crop grown in rotation with sugarcane (*Saccharum* spp. hybrids) in the high organic matter Histosols of the Everglades Agricultural Area (EAA) of south Florida. Weed interference is an important factor limiting lettuce production in the EAA. Lettuce is very sensitive to weed interference because of its short stature and slow growth early in the season. Production of lettuce in the EAA is further limited by a lack of effective PRE and POST herbicides, especially for broadleaf weed control. PRE herbicides available for lettuce grown in mineral soils have reduced activity in high organic matter soils (Dusky et al. 1988). Currently, imazethapyr is the only herbicide registered for PRE and POST broadleaf weed control in lettuce in the EAA under special local needs (SLN) registration (SLN FL-960005). However, imazethapyr provides limited control of problematic weeds, such as common lambsquarters (*Chenopodium album* L.) and causes lettuce injury (Dusky 1990; Dusky and Al-Henaid 1993; Dusky and Stall 1995). As a result, intensive hand labor is used to supplement chemical weed control.

Large amounts of phosphorus (P), an important macroelement, are essential for high-quality lettuce production in P-deficient soils (Alt 1987; Hochmuth et al. 1994; Sanchez et al. 1990). Although P promotes crop growth and development, it may benefit weeds and create a competitive advantage over crops (DiTomaso 1995). Vengris et al. (1955) reported that common lambsquarters and redroot pigweed (*Amaranthus retroflexus* L.) benefited more from P application than did corn (*Zea mays* L.). Shrefler et al. (1994a,b) reported that smooth pigweed (*Amaranthus hybridus* L.) was more aggressive than lettuce was in absorbing P. Similarly, Santos et al. (2004a,b) reported that common purslane (*Portulaca oleracea* L.) and smooth pigweed competed aggressively with lettuce for P. However, the influence of P fertilization on timing of the critical period of weed control (CPWC) in lettuce to maintain optimum crop yield is not known.

The CPWC is the interval in the crop's growth cycle during which weeds must be controlled to prevent yield losses (Zimdahl 2004). It is described by the time interval between two separately measured crop–weed competition components: (1) the critical timing of weed removal (CTWR), the maximum amount of early season weed competition that the crop can tolerate before suffering irrevocable yield reduction; and (2) the critical weed-free period (CWFP), the minimum weed-free period required from the time of planting to prevent unacceptable yield reductions (Knezevic et al. 2002). The CTWR and CWFP are used to determine the beginning and end of the CPWC, respectively, based on an acceptable level of yield loss. Several factors such as environmental conditions, crop genetics, and cultural practices, including tillage, fertilization, seeding rate, and row spacing, can influence the CPWC by affecting weed species composition, weed density, time of weed emergence relative to the crop, and crop and weed growth (Norsworthy and Oliveira 2004). An understanding of the CPWC provides a basis for planning effective weed-control strategies in crops (Knezevic et al. 2002; Swanton and Weise 1991; Van Acker et al. 1993).

Several studies have focused on evaluating the duration of interference effects of a single weed species on lettuce yield. The critical timing of common lambsquarters removal in lettuce has been estimated to be between 5 to 11 d after emergence (Santos et al. 2004d). Santos et al. (2004c) estimated a critical timing of smooth pigweed and common purslane removal in lettuce was between 24 to 34 d and 37 to 47 d, respectively. However, no research, to our knowledge, has been conducted to determine the effect of mixed weed populations and P fertilization on CPWC in lettuce grown in a P-deficient soil. Therefore, the objective of this study was to determine the influence of P fertilization levels on the CPWC in lettuce in the EAA.

Materials and Methods

Field experiments were conducted at the University of Florida Everglades Research and Education Center (EREC) in Belle Glade, FL, in 2010 and 2011 to evaluate the influence of P fertilization on the CPWC in lettuce. The soil type was Dania Muck (Euic, hyperthermic, shallow Lithic Haplosaprists) with a pH of 7.3 and 80% organic matter. Experimental

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Table 1. Weed density and species present after lettuce emergence in 2010 and 2011 at Belle Glade, FL.

Weed species	Weed density 2010	2011
	——plants m^{-2}——	
Common lambsquarters	58	43
Smooth pigweed	43	38
Common purslane	6	11
Goosegrass	54	86
Fall panicum	9	21
American black nightshade	4	0
Common ragweed	13	11
Yellow nutsedge	22	65
Spreading dayflower	0	5

fields were prepared by chisel plowing, followed by disking with a harrow before planting both years. Composite samples from 42 evenly distributed soil cores (3.0 cm in diameter), 15 cm deep, were obtained from each field 1 wk before planting. Plant-available P concentrations in the soil were determined using the ascorbic acid–molybdenum blue method, after shaking 4 ml air-dried soil samples with 50 ml of extractant for 50 min, followed by filtering through a Whatman No. 2 filter paper (Whatman plc, Springfield Mill, James Whatman Way, Maidstone, Kent ME14 2LE, UK) (Ye et al. 2011). Water-extractable P tests revealed 3.0 to 4.0 mg L^{-1} of P in both years, which is considered low levels for lettuce production (Hochmuth et al. 1994). Triple-super phosphate was applied to the fields at 224, 449, and 671 kg P_2O_5 ha^{-1} (equivalent to 98, 196, and 293 kg P ha^{-1}, respectively) before bed pressing. Based on soil analysis, urea and potash were applied to supply 56 kg N ha^{-1} and 170 kg K_2O ha^{-1}, respectively, both years, before pressing fields into 90-cm-wide beds. Two rows of iceberg lettuce '9285' were directly seeded on each bed at a spacing of 30 cm between rows on October 22, 2010, and October 11, 2011, at a seeding rate of 215,000 seeds ha^{-1}. Fields were overhead-irrigated immediately after planting to supply 25 mm of water. Water was subsequently applied by subsurface irrigation from field ditches by maintaining a water table 61 cm below the soil surface (Snyder et al. 1978). Lettuce was thinned to a 30-cm intrarow spacing 1 wk after emergence (WAE) to give approximately 72,000 plants ha^{-1}.

The experimental design was a randomized complete block with a split-plot arrangement and four replications. Main plots consisted of three P fertilization levels (added to the soil at 98, 196, and 293 kg P ha^{-1}) and subplots consisted of increasing duration of weed interference and duration of weed-free periods. Subplots were 90 cm wide by 7.6 m long both years. A naturally occurring population of mixed weed species (Table 1) was removed in a timely manner to obtain appropriate duration of weed interference and the duration of weed-free periods. For each P fertilization level, individual sets of treatments were applied on the subplots to represent both increasing duration of weed interference and the duration of weed-free periods. Emerged weeds were allowed to compete with lettuce for 1, 2, 3, 4, 5, 6, 7, and 8 WAE for the increasing duration of weed interference, and then plots were kept weed-free for the remainder of the season. For the duration of weed-free period, plots were kept free of weeds for 1, 2, 3, 4, 5, 6, 7, and 8 WAE; after which, weeds were allowed to reinfest and compete with the lettuce for the remainder of the season. Additionally, season-long weedy and weed-free controls were included for each P fertilization level. Plots were kept weed-free by hand hoeing at intervals of 1 wk throughout the season. Marketable fresh lettuce were harvested by hand from each plot and weighed to determine yield on January 10, 2011, and December 23, 2012, for lettuce planted on October 22, 2010, and October 11, 2011, respectively.

Statistical Analysis. Actual, marketable, fresh-lettuce yield data for weed-free and weedy experimental plot yields were subjected to ANOVA using the *lme* function in R (R version 2.15.0; R Foundation for Statistical Computing, Wien, Austria) (Pinheiro and Bates 2000) to assess the effect of different P fertilization levels on lettuce yields. The significance of interactions between years and treatment combinations were evaluated at the $P = 0.05$ level (McIntosh 1983). Relative marketable fresh-lettuce yield of individual plots were calculated as a percentage of the corresponding weed-free yield for each P-fertilization level. Nonlinear regression analysis was used to estimate the relative yield of marketable fresh lettuce as a function of increasing duration of weed interference or duration of weed-free period. A four-parameter, log–logistic equation was fitted to assess the effect of increasing duration of interference on marketable fresh-lettuce relative yield and to determine the beginning of the CPWC for each P-fertilization level:

$$Y = [c + (d - c)]/\{1 + \exp[b(\log T - \log e)]\} \quad [1]$$

where Y is relative yield (percentage of season-long, weed-free yield), T is the time expressed as weeks after emergence, b is the slope of the inflection point, c is the lower limit of the curve or the minimum relative yield in the presence of weed interference, d is the upper limit of the curve or the maximum relative yield in the absence of weed interference, and e is the number of weeks after emergence when the inflection point occurs. The three-parameter Gompertz model was used to describe the effect of the increasing duration of the weed-free period on the relative yield of marketable fresh lettuce and to determine the end of CPWC for each P-fertilization level:

$$Y = d|\exp\{-\exp[b(T - e)]\}| \quad [2]$$

where Y is relative yield (percentage of season-long, weed-free yield), T is the time expressed as weeks after emergence, b is the slope of the inflection point, d is the asymptote or maximum relative yield in the absence of weed interference, and e is the number of weeks after emergence when the inflection point occurs. Equations 1 and 2 were fit to the data using the drc package (Ritz and Streibig 2005) of the open-source language R (R Development Core Team 2012). Parameter estimates across years and P-fertilization levels were evaluated to determine whether regressions were nonparallel (Norsworthy and Oliveira 2004), using likelihood ratio tests. Likelihood ratio tests were conducted using the *compParm* function in R to compare whether parameters were different across years or between P fertilization levels. Data were pooled when parameter estimates were constant across years or P fertilization levels and presented separately when parameter estimates were different.

Results and Discussion

Initial weed emergence was simultaneous to lettuce both years. Weed populations in 2010 and 2011 predominately

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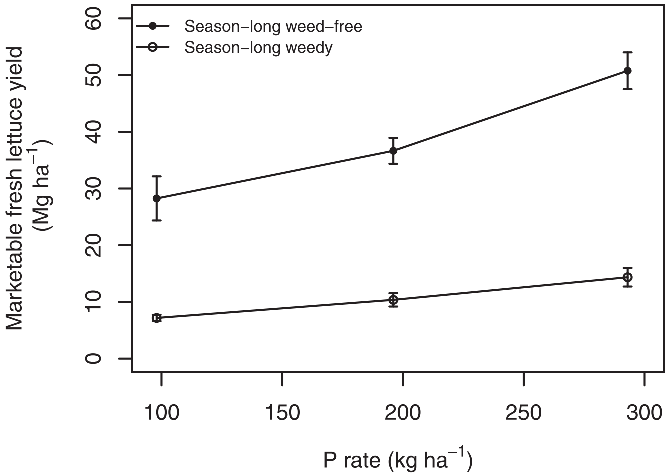

Figure 1. Lettuce yield in response to P fertilization (98, 196, and 293 kg P ha^{-1}) at Belle Glade, FL, combined over 2010 and 2011 in season-long weed-free (●) and season-long weedy (○) experimental units.

comprised common lambsquarters, smooth pigweed, common purslane, goosegrass [Eleusine indica (L.) Gaertn.], fall panicum (Panicum dichotomiflorum Michx.), American black nightshade (Solanum americanum P. Mill.), common ragweed (Ambrosia artemisiifolia L.), yellow nutsedge (Cyperus esculentus L.), and spreading dayflower (Commelina diffusa Burm. f.) (Table 1). Total weed density was 209 and 280 plants m^{-2} in 2010 and 2011, respectively. Common lambsquarters, smooth pigweed, goosegrass, and yellow nutsedge were the most predominant and comprised 85 and 83% of the weed populations in 2010 and 2011, respectively.

There was no P fertilization level by year interaction for either the weed-free ($P = 0.406$) or weedy ($P = 0.137$) lettuce experimental plot yields; therefore, data were pooled over years. Both weed-free and weedy-yield lettuce increased with increasing P fertilization levels. Weed-free marketable fresh-lettuce yields were 28.3, 36.6, and 50.7 Mg ha^{-1}, whereas weedy marketable fresh-lettuce yields were 7.2, 10.4, and 14.3 Mg ha^{-1} for 98, 196, and 293 kg P ha^{-1}, respectively (Figure 1). Lettuce has been reported to have a positive yield response to P fertilization in P-deficient soils (Nagata et al. 1992; Sanchez and Burdine 1988). The average marketable fresh lettuce yield is 34 Mg ha^{-1} in the P-deficient soils in the EAA following P application based on soil-test fertilization recommendation. Season-long interference of mixed weed species in the weedy plots resulted in up to a 75% yield reduction. In contrast, lettuce yield reduction as a result of season-long interference of single weed species, such as common purslane, smooth pigweed, and common lambsquarters, was 27, 30, and 52%, respectively (Santos et al. 2004b, 2004d; Shrefler et al. 1994a).

The log–logistic (Equation 1) and Gompertz (Equation 2) models provided good fits to estimate the influence of P fertilization on the beginning and end of the CPWC in lettuce, respectively. Goodness-of-fit for the curves was evaluated using root mean square errors (Table 2). A test of lack-of-fit at the 95% level was not significant for the curves, indicating that the regression models were appropriate (Ritz and Streibig 2005). Comparison of the log–logistic (Equation 1) and Gompertz (Equation 2) models indicated that relative yield response of marketable fresh-lettuce to the duration of weed interference and the duration of the weed-free period, respectively, were not consistent among P fertilization levels ($P = 0.03$ and 0.02 for duration of weed interference and duration of weed-free period, respectively). In addition, the relative yield response of marketable fresh-lettuce to the duration of weed interference and the duration of the weed-free period within P fertilization level was consistent among years ($P = 0.507$ and 0.572 for the duration of weed interference and the duration of weed-free period, respectively). Consequently, data were pooled by year within each P fertilization level (Figure 2). Coefficients for the parameters used to fit the log–logistic and Gompertz models are listed in Table 2.

A 5% yield-loss level of acceptable, marketable fresh lettuce was used to determine the influence of P fertilization on both the beginning and the end of the CPWC. The 5% acceptable yield-loss level has been used in similar studies to determine the CPWC in field and sweet corn, peanut (*Arachis hypogaea* L.), soybean [*Glycine max* (L.) Merr.], and lentil (Lens culinaris Medik.) (Evans et al. 2003; Everman et al. 2008; Knezevic et al. 2002; Norsworthy and Oliveira 2004; Smitchger et al. 2012; Van Acker et al. 1993; Webster 2007; Williams 2006). Determination of the acceptable yield-loss level depends on the cost of weed management in relation to the yield benefit achieved by the grower. The 5% yield loss is acceptable to lettuce growers and the economics of lettuce production. The CPWC in lettuce averaged over 2010 and 2011 was estimated to be 4.6, 3.4, and 2.3 wk at 93, 196, and 293 kg P ha^{-1} at 5% yield-loss level.

The beginning of the CPWC in lettuce was estimated to be 2.2, 2.3, and 2.9 WAE at 93, 196, and 293 kg P ha^{-1}, respectively, at the 5% yield-loss level, which corresponded to the four- to six-leaf stage of lettuce development. The beginning of the CPWC was delayed at the highest P fertilization level, indicating lettuce tolerance to weed interference as P fertilization level increased. Shrefler et al. (1994b) reported an increase in lettuce competitiveness as P

Table 2. Parameter estimates (SE) for the four-parameter log–logistic model and three-parameter Gompertz model characterizing the influence of different levels of P on the duration of weed interference and the duration of weed-free period on relative lettuce yield, respectively.[a,b]

P level	Log–logistic					Gompertz			
kg ha^{-1}	*b*	*c*	*D*	*e*	RMSE	*b*	*d*	*e*	RMSE
98	3.2 (1.3)	21.2 (15.2)	100.6 (5.5)	4.9 (0.8)	20.5	−0.5 (0.1)	101.1 (4.5)	1.1 (0.2)	15.7
196	3.7 (1.3)	18.5 (11.8)	99.1 (4.3)	5.1 (0.5)	16.5	−0.6 (1.0)	100.4 (4.1)	0.6 (0.2)	17.5
293	5.6 (1.6)	25.8 (5.3)	98.9 (3.5)	4.9 (0.3)	15.1	−0.6 (0.1)	99.8 (2.8)	0.5 (0.2)	12.6

[a] Log–logistic: $[Y = c + (d - c)]/1 + \exp\,[b(\log T - \log e)]$, where *Y* is relative yield (percentage of season-long weed-free), *T* is the time expressed as weeks after emergence of lettuce, *b* is the slope of the inflection point, *c* is the lower limit, *d* is the upper limit, and *e* is the number of weeks after emergence when the inflection point occurs. Gompertz: $Y = d[\exp\{-\exp[b(T - e)]\}]$, where *Y* is the relative yield (percentage of season-long weed-free), *T* is time expressed as weeks after emergence, *b* is the slope of the inflection point, *d* is the asymptote, and *e* is the number of weeks after emergence when the inflection point occurs.

[b] Abbreviation: RMSE, root mean square error.

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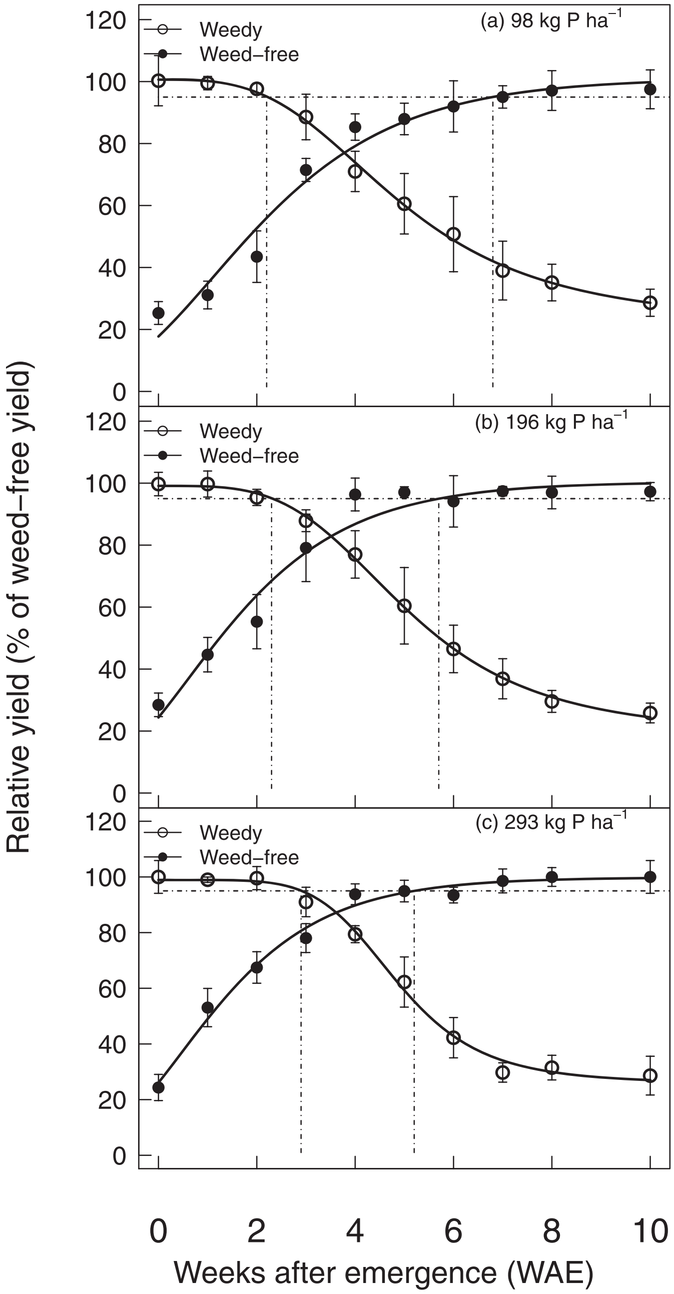

Figure 2. The influence of three levels of P (98, 196, and 293 kg P ha^{-1}) on the duration of weed interference (○) and the duration of weed-free period (●) on relative lettuce yield combined over 2010 and 2011 at Belle Glade, FL. Equations 1 and 2 were used to predict the duration of weed interference and the duration of weed-free period on relative lettuce yield, respectively.

fertility increased at low weed densities, which is synonymous with small weed sizes and low densities early in the season. Roberts et al. (1977) reported no lettuce yield loss from interference of mixed weed populations when lettuce was kept weed-free from 3 wk after planting. However, regardless of the P fertilization level, the relative yield loss of lettuce increased over time. Shrefler et al. (1994b) reported that at high weed density, lettuce became less competitive regardless of additional P, which is synonymous with large weed sizes as the growing season progressed. Season-long weed interference resulted in 71, 75, and 73% lettuce-yield loss at 93, 196, and 293 kg P ha^{-1}, respectively. Shrefler et al. (1994a) reported 20% decrease in lettuce yield after 7 wk of interference from smooth pigweed at 125 kg P ha^{-1} level. The mechanisms by which weed interference reduce lettuce yield, even at high P levels, is attributed to light interception by a tall weed canopy and absorption of P from the soil (Santos et al. 2004a).

The end of the CPWC in lettuce was 6.8, 5.7, and 5.2 WAE at 93, 196, and 293 kg P ha^{-1}, respectively, at 5% yield-loss level, which corresponded to the cupping to heading stage of lettuce development. The decrease on the end of CPWC with increased P fertilization may be attributed to rapid growth of lettuce in the absence of weeds, which resulted in lettuce competitiveness with late-emerging weeds. Rapid corn growth under high-fertility levels result in higher crop leaf area index (LAI), which reduces light quality and quantity reaching the lower canopy, thus impeding emergence, establishment, and growth of subsequent weeds cohorts (Teasdale 1995). Lettuce yield has been reported to show a positive linear response with increase in P fertilization under weed-free conditions (Nagata et al. 1992). In addition, lettuce competitiveness with smooth pigweed has been reported to increase as P levels increased (Shrefler et al. 1994b). Similarly, Evans et al. (2003) reported a decrease in the length of the duration of weed-free period in corn as N levels increased because of rapid canopy closure resulting from higher crop LAI.

Our research shows that P fertilization influences the CPWC in lettuce in a P-deficient soil. The results indicate that CPWC in lettuce varied from 2.3 to 4.6 wk, depending on P fertilization level. The onset of the CPWC in lettuce was delayed at the highest P fertilization level, with inadequate P fertilization resulting in a 2.3-wk shift to earlier in the season yield loss. Knowledge of the influence of P fertilization on CPWC in lettuce could improve weed management in P-deficient soils. This study shows that inadequate levels of P fertilization in lettuce result in the need for earlier, more-intensive weed management systems. However, even high levels of P fertilization (e.g., 293 kg P ha^{-1}) do not eliminate the need for timely application of effective POST herbicides and intensive hand weeding.

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