

Crop-Weed Relationships in Okra [*Abelmoschus esculentus* (L.) Moench], Soybean (*Glycine max* L.) and Maize (*Zea mays* L.) in the Middleveld of Swaziland

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Abstract: The effects of okra [*Abelmoschus esculentus* (L.) Moench], soybean (*Glycine max* L.) and maize (*Zea mays* L.) on weed growth were examined in a field experiment carried out at Luyengo (26°34'S; 31°12'E) in the Middleveld of Swaziland. The aim was to check consistency of competitiveness of crops under different weed removal regimes. Two series of weed removal treatments were included. In the first series, treatments of increasing duration of weed control were maintained weed-free until 3, 7 or 11 weeks after emergence of the crops. The weeds were subsequently allowed to develop till crop harvest. In the second series, weeds were allowed to develop with the crops from emergence until 3, 7 or 11 weeks after crop emergence; then the plots were kept weed-free till harvest. The weed species *Oxalis latifolia*, *Cyperus esculentus*, *Amaranthus hybridus*, *Ipomoea purpurea* and *Nicandra physaloides* occurred throughout the different weed-infested and weed-free interference durations. *Commelina benghalensis* and *Acanthospermum hispidum* were particularly predominant under increasing weed infestation treatments. The similarity matrix based on Jaccard's coefficient showed that the composition of weeds under weed-free treatments in soybean was not identical to that of maize and okra, respectively. Further, the weed flora was not homogenous under different lengths of weed-free period showing the combined influence of weed removal and crop on the composition of weed infestation. There were no significant differences in the prevalence of weeds with either C₃ or C₄ photosynthetic pathways associated with the three crops. A longer equality point of weed control and interference, and lower regression coefficient between weed biomass and yield for soybean compared to maize and okra suggested decreased sensitivity of soybean to weed interference. The results indicate potential for competitive crop genotypes such as soybean for use in intentionally designed cropping systems to augment weed control practices.

Keywords: Critical Period, Crop-Weed Competition, Photosynthetic Pathway, Weed Biomass, Weed Density, Weed Interference, Weed Species Composition

1. Introduction

In smallholder agriculture in the Southern Africa region, weed control has not been successful owing to lack of widespread use of herbicides or mechanical weeding practices, and, lack of crop rotations accompanied by continuous maize-based cultivation methods [1]. Farmers are thus beset with moribund weed control practices and intractable agronomic weed complexes. Yet, while farmers are being encouraged to adopt chemical weed control [2],

elsewhere in developed agriculture, the sustained use of herbicides has resulted in shifts in the weed-flora of arable fields or increasing environmental and public health concerns over their use [3, 4]. As a consequence, the age-old integrated approach to weed management that support judicious use of herbicides remains pivotal, but with incessant challenges related to quality of recommendations to and ease of use by farmers [2]. In Swaziland, herbicide are not conventionally used for weed control whereas manual and mechanical methods are inadequately employed [5]. Adoption of other

strategies leading to an increase in the competitive ability of the crop could be a feasible way to suppress weed populations.

The weed species composition and distribution of any given area are influenced by environmental and biological factors that determine the habitat type [6]. This is further predisposed by human efforts to control weeds in a crop giving them some kind of demographical advantage in time and place if insufficiently accomplished. In terms of numbers and time in which marked changes may occur, changes brought about by production practices are considered the most important for weed management [6, 7]. Each new crop production or managerial practice will ultimately have its own complement of weeds. The present study concurred with [8] who argued that often, the tendency is overly concern with the depressing effect of weeds on crops without concomitant examination of composition of the weed community. However, while the make-up of a weed community is indicative of the efficacy of changes to environment and production practices, the crop genotypes grown are an important factor in competitiveness towards weeds [9]. It is important to understand effect of opportunities provided by each crop genotype for weed establishment.

Park *et al.* [10] suggested that if the intrinsic weed-suppressing ability of a crop is to be exploited, it is necessary to identify the ecological and life-history traits of weeds that confer competitive ability. The most common traits considered are the relative time of emergence, leaf area and biomass. It is intimated that weed management decision should further be evaluated from the perspectives of biological accuracy. To this effect, [11] suggested that crop tolerance through toleration of depleted resources and continuation of growth may be measured by crop growth or dry matter accumulation whereas weed biomass or weed number are a measure of resource competition by crop suppression of weeds through rapidly depleting resources. In order to demonstrate the potential for crop genotypes to suppress weeds and to evaluate the potential for such a strategy for low-input cropping practices, two field experiments were performed with okra [*Abelmoschus esculentus* (L.) Moench], soybean (*Glycine max* L.) and maize (*Zea mays* L.) under variable time of weed removal.

2. Materials and Methods

2.1. Experimental Site

The experiment was carried out on Malkerns soil series M-set at Luyengo in the Middleveld of Swaziland. The site is located at latitude 26°34'S and longitude 31°12'E and an altitude of 750 meters above sea level. The mean annual rainfall is 980 mm of which 83 per cent falls between October and March. The mean temperature is 21.4°C [5].

2.2. Experimental Procedures

Naturally occurring weed populations were exploited in

the experiments. Two series of weed removal treatments were included. In the first series, treatments of increasing duration of weed control were maintained weed free until 3, 7 or 11 weeks after emergence of the crops. The weeds were subsequently allowed to develop until final harvest when they were removed. In the second series, weed interference treatments of varying duration allowed weeds to compete with the crops from emergence until 3, 7 or 11 weeks after crop emergence; then the plots were weeded and kept weed-free until harvest. Similar methods have been used by other researchers [12].

The two experiments were laid out in randomized complete block design with treatments arranged in a 3 (crops) x 3 (weed removal) factorial scheme with three replications. The gross plot sizes were 6.0 m x 3.6 m for all plots. The crop varieties grown were SC621 (Seed-Co®, Zimbabwe) for maize, Tgx36x/1989 for soybean and, Clemson spineless for okra. Maize was planted at a spacing of 0.9 m x 0.25 m, okra at 0.60 m x 0.45 m and soybean at 0.50 m x 0.10 m. Compound fertilizer 2:3:2 (22% N) was basal applied at 300 kg ha⁻¹ to both maize and okra. LAN (28% N) fertilizer was top-dressed at 100 kg ha⁻¹ and 40 kg ha⁻¹ in the maize and okra crops, respectively. Soybean received basal application of single super phosphate at 400 kg ha⁻¹.

2.3. Data Collection

Weed dry mass, density, identification and species composition were determined at 3, 7, 11 weeks after emergence of the crops before the weeding treatments scheduled for the periods were implemented. Weeds were cut at the soil surface from a plot of 0.25 m² in the center of the crop rows. For identification, weeds of up to 5 cm in height were considered. Weed identification was based on botanical keys supported by regional field identification guides [13, 14]. Weed density was the number of plants rooted within each quadrat. Counted weeds were oven-dried at 80 °C for 48 hours and weighed to obtain weed biomass. Both weed biomass and density per quadrat were extrapolated to a square meter. Weed species composition was computed using the Jaccard index value [15] based on the formula:

$$J = c / (a + b + c) \quad (1)$$

where J = Jaccard similarity index; a = total number of weed species in crop "a"; b = total number of weed species in crop "b"; c = total number of weed species common to crop "a" and "b". The physiological similarities of crops and weeds was based on ascertaining the photosynthetic pathways of crops and weeds as shown in Table 1. Soybean is a C₃ crop while okra and maize are C₄ crops.

Singh *et al.* [12] described two approaches commonly used to determine the critical period of weed control as being: (i) critical weed-free period called the minimum time point under weed-free and (ii) critical period of weed infestation called the maximum time point under weed infestation. The time interval between the minimum and maximum time

points has been defined as a critical period for weed control [16]. In addition, the crossing point of the two periods has been called the equality point of control and interference and this parameter was used in this trial. The point determines the equality of increasing or decreasing crop yield in response to competitive conditions [12].

Okra fruits were harvested market-ready five times beginning 10 weeks after planting. Yield was expressed as fresh weight. Maize was harvested 16 weeks after planting from 2.5 m x 5.0 m net plots and grain yield was standardized to 12.5 per cent moisture content. Similar procedures for determining yield were followed for soybean which was harvested 22 weeks after planting with yield being adjusted to 8 per cent moisture content.

2.4. Statistical Analysis

Data were analyzed by ANOVA using Genstat Version 8 (USA). The two experiments were analyzed separately. Means were separated using Fisher's least significant difference (LSD) at $P < 0.05$. To homogenize variances, data

on weed density and weed numbers were square root transformed before statistical analysis. Data are presented as untransformed means. Linear regression relationships between weed biomass and crop yield were determined for weedy period and weed-free period, respectively. Slope of linear regression (regression coefficient) was considered a measure of sensitivity of crop yield to period crops tolerated weeds and weed-free period required by crops.

3. Results

3.1. Weed Species Composition

A total of 17 weed species/taxa were encountered, of which 11 were annuals, 1 biennial and 5 perennials comprising 3 grasses, 1 sedge and 13 broadleaf weeds (Table 1). The weed species represented 10 families among which the Asteraceae family had the highest number of weed species (5). The study identified 8 species with C_4 photosynthetic pathway and 9 species with C_3 pathway.

Table 1. Genera, life cycle and photosynthetic pathways of weeds observed in the experiments.

Family name	Scientific name	Common name	Life cycle	Photosynthetic pathway
Grasses				
Poaceae	<i>Eleusine indica</i> (L.) Gaertn	Goose grass	A	C_4
	<i>Cynodon dactylon</i> (L.) Pers.	Bermuda (Star) grass	P	C_4
	<i>Perotis patens</i>	Bottlebrush grass	A	C_4
Sedges				
Cyperaceae	<i>Cyperus esculentus</i> (L.)	Yellow nutsedge	P	C_4
Broadleaved				
Amarantaceae	<i>Amaranthus hybridus</i> (L.)	Common pigweed	A	C_4
Euphorbiaceae	<i>Euphorbia heterophylla</i> L.	Milkweed	A	C_4
Convolvulaceae	<i>Ipomea purpurea</i> (L.) Roth	Morning glory	P	C_3
Asteraceae	<i>Acanthospermum hispidum</i> (DC.)	Bristly starbur	A	C_3
	<i>Bidens pilosa</i> (L.)	Blackjack	A	C_3
	<i>Tagetes minuta</i> (L.)	Mexican gold	A	C_3
	<i>Galinsoga parviflora</i> (Cav.)	MacDonald Eye	A	C_3
	<i>Schkuhria pinnata</i> (Lam.) Kentze ex Thell	Dwarf marigold	A	C_3
Rubiaceae	<i>Richardia scabra</i> (L.)	Rough Mexican clover	P	C_4
Solanaceae	<i>Nicandra physaloides</i> (L.) Gaertn.	Apple of Peru	A	C_3
Commelinaceae	<i>Commelina benghalensis</i>	Wandering Jew	P	C_3
Portulacaceae	<i>Portulaca oleracea</i> (L.)	Common purslane	A	C_4
Oxalidaceae	<i>Oxalis latifolia</i> (Kunth)	Broadleaf woodsorrel	B	C_3

Note: A = annual; B = biennial; P = perennial

Figure 1 shows the weed species prevalent at three sampling times for the treatments under increasing duration of weed infestation (weedy) and length of weed-free period (weed-free), respectively. The species *Oxalis latifolia*, *Cyperus esculentus*, *Amaranthus hybridus*, *Ipomoea purpurea* and *Nicandra physaloides* occurred throughout the different weed-infested and weed-free interference durations. On the other hand, *Bidens pilosa*, and *Schkuhria pinnata* were prevalent in the three weed-free set of treatments but only in the 7 and 11 weeks' treatments under the weed-infested set. *Commelina benghalensis* and *Acanthospermum hispidum* were particularly predominant under increasing weed infestation.

The similarity matrix based on Jaccard's coefficient seen in Table 2 showed that the composition of weeds under increasing duration of weed infestation was homogenous, that is, there was a level of similarity in species composition of weed floras for comparisons carried out amongst the three crops. Under weed-free treatments, however, indices of less than 0.5 between soybean and maize and okra, respectively, showed that the composition was not identical. In Table 3, the Jaccard's coefficient in the range of 0.5 to 0.73 showed homogeneity in weed flora at different durations of weed infestation. Indices of 0.33 to 0.43 under weed-free treatments showed that the weed flora was not identical in different durations of weed infestation.

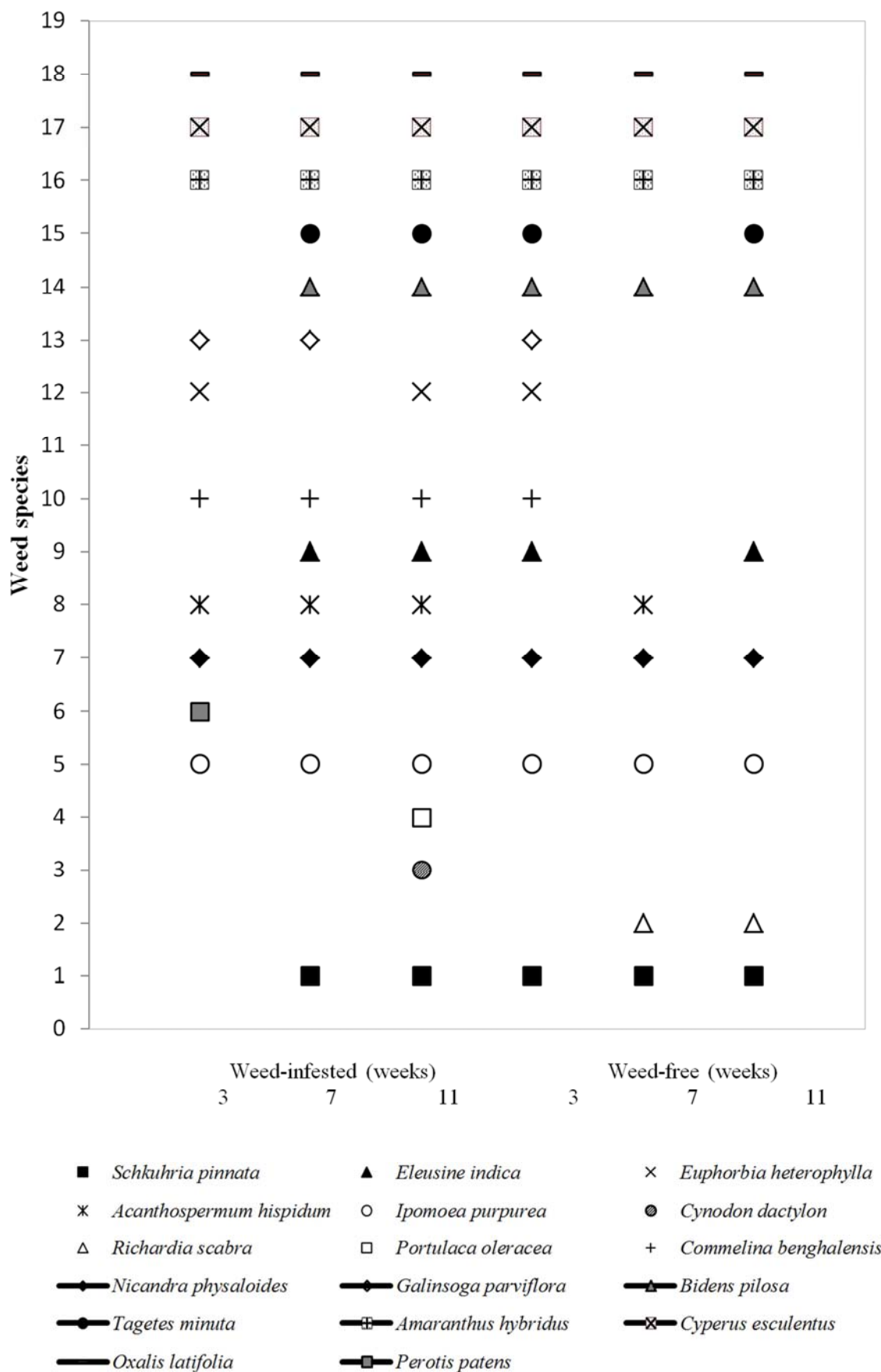


Figure 1. Seasonal prevalence of weed species under increasing duration of weed infestation and increasing length of the weed-free period.

Table 2. Similarity matrix of weed species amongst crops based on Jaccard's similarity coefficient.

Crops	Weed-infested treatments			Weed-free treatments		
	Maize	Okra	Soybean	Maize	Okra	Soybean
Maize	1.00	0.80	0.73	1.00	0.83	0.39
Okra		1.00	0.69		1.00	0.39
Soybean			1.00			1.00

Table 3. Similarity matrix of weed species amongst based on Jaccard's similarity coefficient.

Duration of weed interference	Weed-infested treatments			Weed-free treatments		
	3 weeks	7 weeks	11 weeks	3 weeks	7 weeks	11 weeks
3 weeks	1.00	0.62	0.50	1.00	0.43	0.33
7 weeks		1.00	0.73		1.00	0.39
11 weeks			1.00			1.00

3.2. Physiological Relationships Amongst Weed Species and Crops

There were no significant differences in the prevalence of weeds with either C₃ or C₄ photosynthetic pathways amongst the three crops under either increasing duration of weed infestation (Table 4) or increasing length of weed free period (Table 5). However, the negative sign of contrasts in Table 4 showed that maize subtended less C₃ weed species compared to okra and soybean crops while C₃ weed species were less

prevalent in soybean than in okra. The positive sign of contrasts showed the contrary for C₄ weed species; that is, maize subtended slightly more C₄ weed species compared to okra and soybean crops while the species were more prevalent in okra than soybean (Table 4). In Table 5, under increasing length of weed-free period, the positive sign of contrasts showed that both C₃ and C₄ weed species appeared to be more prevalent in maize compared to okra and soybean crops, and more prevalent in okra compared to soybean, respectively.

Table 4. Prevalence of weeds with C₃ or C₄ photosynthetic pathways recorded under increasing duration of weed infestation in the three crops.

Photosynthetic pathway	(I) Crop	(J) Crop	Mean Difference (I-J)	Std. Error	Significance
C ₃ pathway weed species	Maize ¹	Okra ¹	-0.03608	0.19304	0.853 ns
	Maize	Soybean ²	-0.04819	0.19304	0.805 ns
	Okra	Soybean	-0.01211	0.19304	0.951 ns
C ₄ pathway weed species	Maize	Okra	0.09205	0.12724	0.476 ns
	Maize	Soybean	0.22495	0.12724	0.090 ns
	Okra	Soybean	0.13291	0.12724	0.307 ns

*, **, ns, Significant at the 0.05, 0.01, and non-significant at the 0.05 level of probability, respectively

^{1/} C₄ photosynthetic pathway, ^{2/} C₃ photosynthetic pathway

Table 5. Prevalence of weeds with C₃ or C₄ photosynthetic pathways recorded under increasing length of weed free period in the three crops.

Photosynthetic pathway	(I) Crop	(J) Crop	Mean Difference (I-J)	Std. Error	Significance
C ₃ pathway weed species	Maize ¹	Okra ¹	0.03694	0.13973	0.794 ns
	Maize	Soybean ²	0.18891	0.13973	0.189 ns
	Okra	Soybean	0.15197	0.13973	0.288 ns
C ₄ pathway weed species	Maize	Okra	0.11111	0.26165	0.675 ns
	Maize	Soybean	0.15713	0.26165	0.554 ns
	Okra	Soybean	0.04602	0.26165	0.882 ns

, *, ns, Significant at the 0.05, 0., and non-significant at the 0.05 level of probability, respectively

^{1/} C₄ photosynthetic pathway, ^{2/} C₃ photosynthetic pathway

3.3. Relationship Between Weed Density, Biomass and Crop Yield

Under increasing duration of weed infestation and for each crop, weed densities were inversely associated with biomass while higher crop yields were associated with lower weed biomass (Table 6). In okra, fruit yield did not significantly differ amongst treatments with different durations of weed infestation although there were significant differences in weed biomass. For soybean, grain yield significantly differed amongst treatments while weed biomass under 11-weeks of weed-infestation was significantly different from the other two treatments. In maize, the trend of results was similar to

okra with no significant yield differences amongst treatments but with 11-weeks of weed-infestation subtending the highest weed biomass.

There were fewer weeds, lower weed biomass and higher crop yields with increasing length of the weed-free period (Table 6). In okra, keeping the crop weed-free beyond 7 weeks showed significant reduction in weed biomass while fruit yield was not significantly different between the 7-week and 11-week weed-free durations. In soy bean and maize, each incremental length of the weed-free period significantly reduced weed biomass as well as improved crop yield.

Table 6. Weed density, weed biomass and crop yield response to duration of weed interference or increasing length of weed-free period.

Crops	Increasing duration of weed infestation				Increasing length of weed-free period			
	Period weedy (weeks)	Weed density (n/m ²)	Weed biomass (kg/ha)	Crop yield (kg/ha)	Period weedfree (weeks)	Weed density (n/m ²)	Weed biomass (kg/ha)	Crop yield (kg/ha)
Okra	3	518.7 ^a	41.9 ^a	2240.7 ^c	3	96.0 ^a	216.3 ^a	914.18 ^a
	7	482.7 ^a	243.7 ^b	1160.2 ^b	7	60.0 ^a	180.3 ^a	2325.93 ^{bc}
	11	185.3 ^b	478.7 ^c	463.4 ^a	11	20.0 ^a	19.1 ^b	2360.03 ^c
Soybean	3	296.0 ^a	17.3 ^a	927.0 ^c	3	77.3 ^a	248.1 ^c	389.66 ^a
	7	269.0 ^a	222.7 ^a	553.7 ^b	7	17.3 ^b	172.3 ^b	709.22 ^b
	11	138.7 ^a	338.0 ^b	276.1 ^a	11	13.3 ^b	13.3 ^a	998.29 ^c
Maize	3	396.0 ^a	13.7 ^a	8564.5 ^b	3	113.3 ^a	257.7 ^a	3329.83 ^a
	7	736.0 ^a	181.7 ^a	4565.6 ^a	7	57.3 ^{ab}	151.7 ^b	7171.20 ^b
	11	228.0 ^a	704.7 ^b	2486.2 ^a	11	20.0 ^{ac}	39.4 ^c	11513.03 ^c

The interaction effects between crops and duration of weed infestations on weed density and biomass were significant and are shown in Figure 2 as Pareto charts which plot data in descending order of values. Weed densities and biomass were overall lower in weed-free treatments compared with weed-infested treatments. Treatments with short period of weed interferences concomitant with crop emergence (weedy for 3

weeks and weed-free remainder of crop duration) had higher weed densities compared to those that were weed-free for 3 weeks and weedy for remainder of crop duration (Figure 2a and 2b). Long duration of 11 weeks under weed infestation (Figure 2a) showed lower weed densities compared to long duration of weed infestation (weed-free for 3 weeks) under weed-free conditions (Figure 2b).

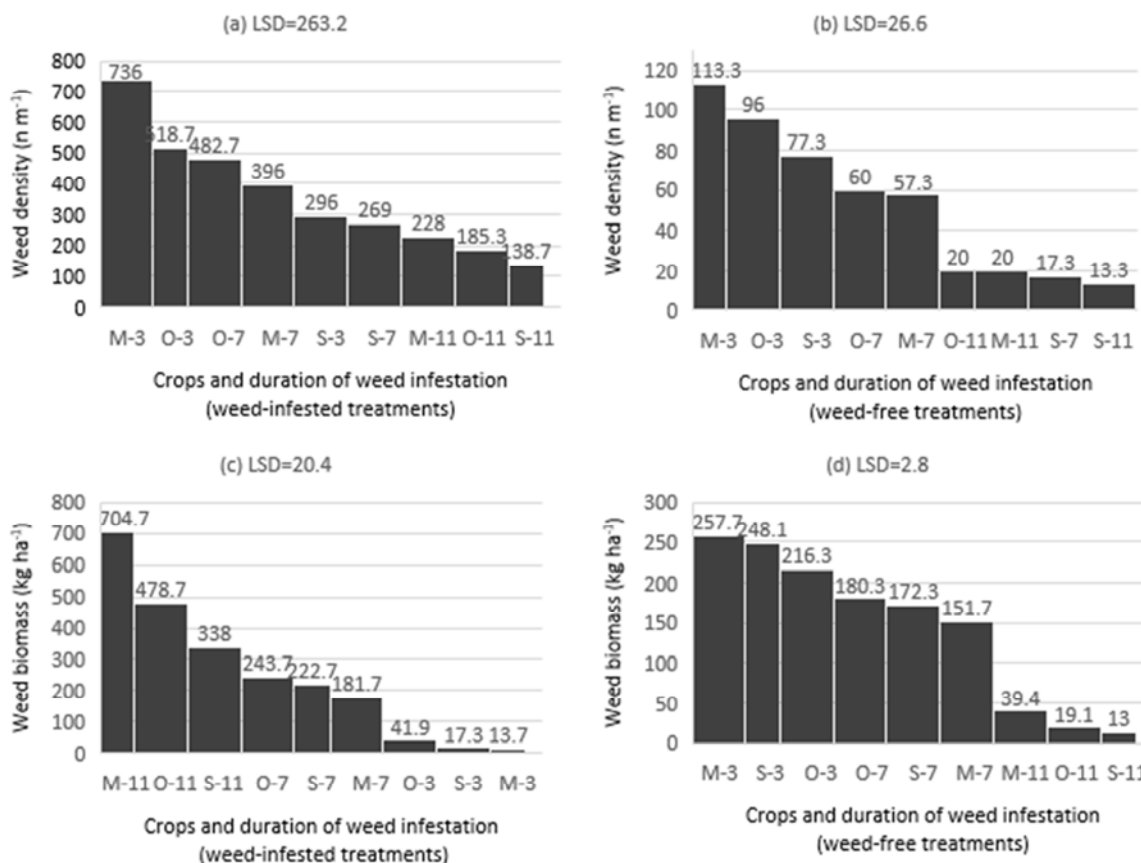


Figure 2. Interaction effects between crops and duration of weed infestations on weed density and weed biomass. Note: M=maize, O=Okra, S= soybean; 3=3 weeks, 7=7 weeks, 11=11 weeks.

Invariably, treatments with increasing duration of weed infestation (weedy for 11 weeks or weed-free for 3 weeks) had greater weed biomass compared to those with shorter duration of weed interference (Figure 2c and 2d). However, under weed-infested conditions, unlike under weed-free conditions, greater numbers of weeds did not translate into

greater biomass. Compared to other crops, maize at 11 weeks of weed infestation or 3 weeks of weed-free conditions, tended to have the greatest weed numbers and weed biomass. Okra subtended greater range of weed densities and biomass particularly at both 3 and 7 weeks of weed infestation or weed-free conditions, unlike maize and soybean.

Figures 3 shows the linear regression relationships between weed biomass and crop yield determined for the weedy period on the left and weed-free period on the right for okra, soybean and maize, respectively. Except for the R-value of 0.43 between weed biomass and okra yield under weed-free regime (Figure 3B), the rest of R-values were between 0.79 and 0.99 under either weedy period or weed-free periods for the three crops. The slopes of linear

regression, under weedy regime and weed-free period were greater for maize compared to the other crops. Conversely, soybean yield showed less sensitivity to weed pressure/removal compared to maize and okra on account of lower slopes of linear regression. In addition, the range of weed biomass in soybean was similar between weed-infested treatments (Figure 3C) and weed-free treatments (Figure 3D) and the converse was evident in okra and maize, respectively.

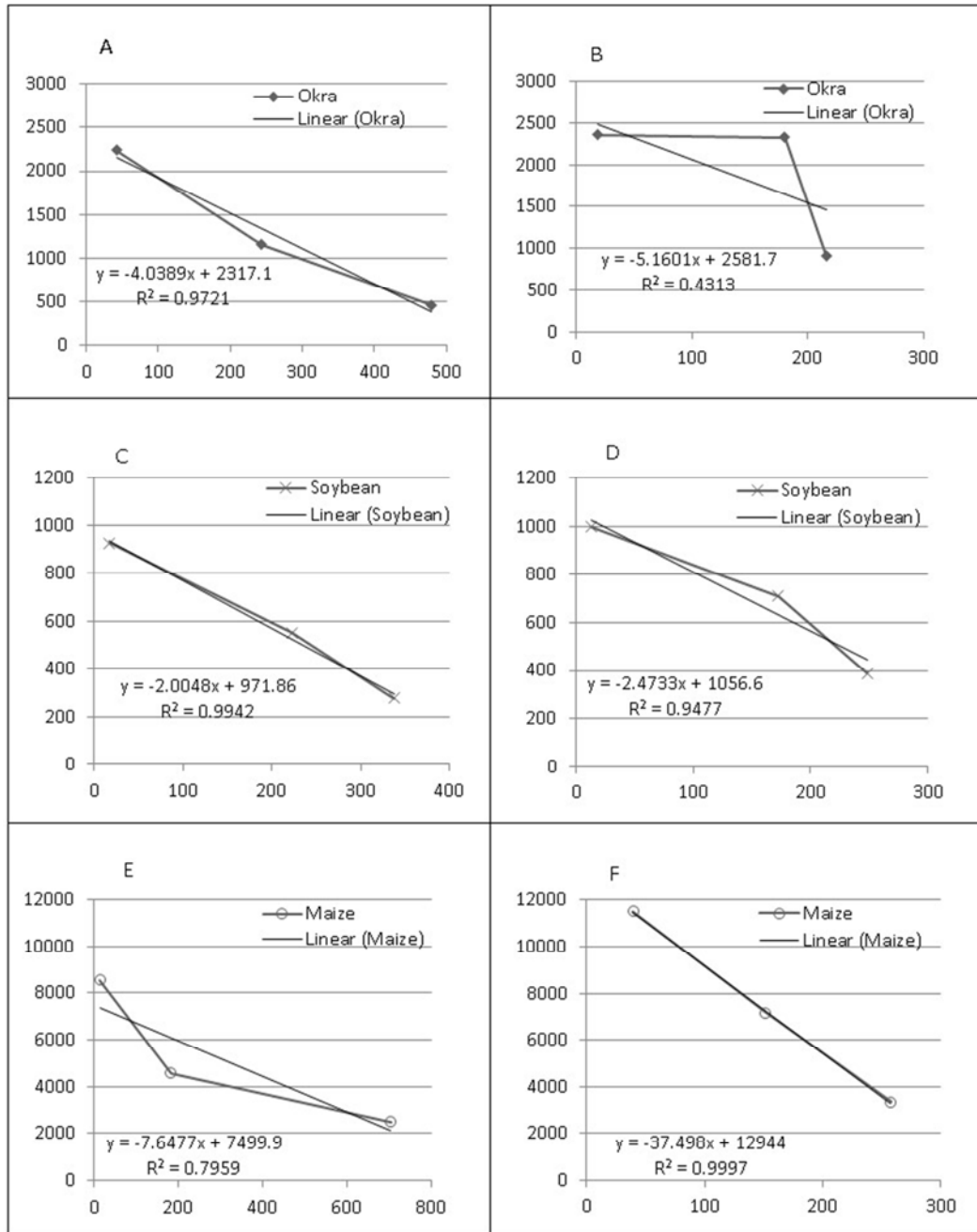


Figure 3. Liner regression of crop yield at harvest versus weed biomass for weed-infested (left) and weed-free (right) durations for okra (A, B), soybean (C, D) and maize (E, F).

3.4. Critical Period of Weed Interference

The intersection of line plots of yield against increasing duration of weed infestation and length of weed-free period, respectively, were used to identify the equality point of

control and interference or conventionally, the critical period of weed interference (Figure 4). For okra, the critical period was 36 days, while for soybean and maize, it was 43 and 40 days, respectively.

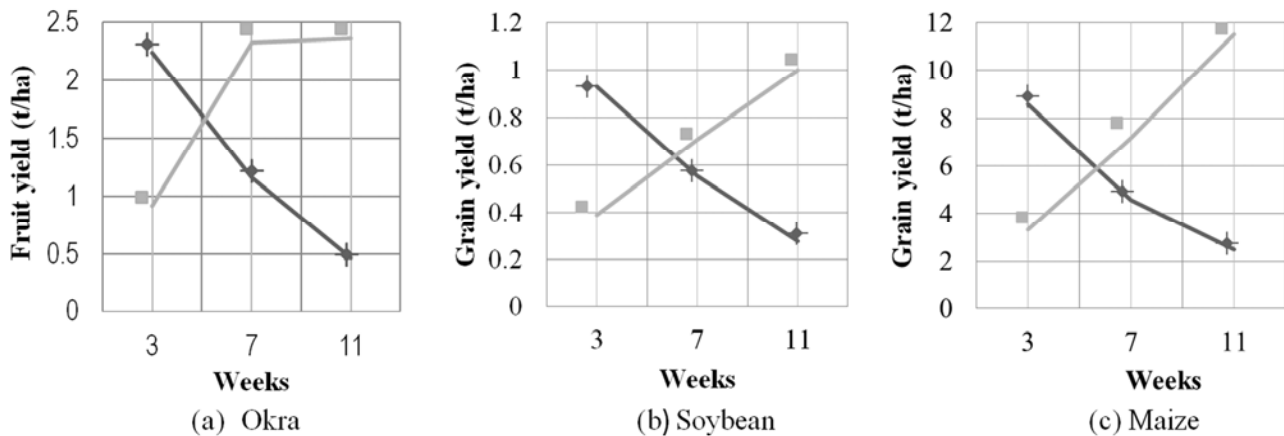


Figure 4. Equality point of control and interference in (a) okra, (b) soybean and (c) maize determined at the intersection of line plots of yield against increasing duration of weed infestation period (♦) and length of weed-free period (■), respectively.

4. Discussion

4.1. Weed Species Composition

The preponderance of annual weeds, more so, annual broadleaf weeds evident in this study has been shown to be akin to high disturbance environments that favor them [17]. The results also showed that some weeds with extensively ecological need can grow in different spatial and temporal niches. The species *Oxalis latifolia*, *Cyperus esculentus*, *Amaranthus hybridus*, *Ipomoea purpurea* and *Nicandra physaloides* occurred throughout the different weed-infested and weed-free interference durations.

It has been inferred that weed species diversity within weed communities is of agronomic significance because of its indicative of the response of weed species to crop and soil management [18]. Using data sets relating to maize, soybean and durum wheat to analyze variability of duration of tolerated competition and weed free period in different geographic regions, [19] reported that relationships between time of weed removal and crop yield depended more on crop characteristics than on the composition of weed infestation. The data lend support for the hypothesis of weed-suppressing ability of the crops as well as time to weed removal, on the composition of weed infestation. The similarity matrix based on Jaccard's coefficient showed that the composition of weeds under weed-free treatments in soybean was not identical to that of maize and okra, respectively. Further, the weed flora was not homogenous under different lengths of weed-free period showing the combined influence of weed removal and crop on the composition of weed infestation.

4.2. Physiological Similarity of Crops and Weeds

The physiological similarities of crops and weeds was based on evaluating the photosynthetic pathways of crops and associated weeds. Of the 17 weed species/taxa encountered, 8 species were identified with the C_4 photosynthetic pathway while 9 species possessed the C_3 pathway. Maize and okra are C_4 species while soybean is a

C_3 plant. Using contrasts, under increasing duration of weed infestation, maize subtended less C_3 weed species compared to okra and soybean crops while these species were less prevalent in soybean than in okra. The positive sign of contrasts showed the contrary for C_4 weed species. It is considered [20] that since more than 95% of plant species belong to C_3 family, the major C_3 crop plants, such as soybean in the present study, would have a competitive advantage over weed species because the crops have been selectively bred for yield. Other researchers report the contrary that crops in general terms do not present high competitive ability against weed species, due to the genetic refinement they were submitted to increase the occurrence of desired productive features in detriment of aggressiveness [15].

The results do also demonstrate that increasing duration of weed infestation with associated weed-weed pressure, may have resulted in C_4 weed species overcoming C_3 weed species. In the different lengths of weed-free period, later emergence of weeds following initial removal may have reduced the weed-weed pressure allowing infestations of both C_3 and C_4 weed species but with the latter showing slight dominance. The implications are that prevailing cultivation practices in the study area appear to favor establishment of C_4 weed species that comprised all the grasses and sedges recorded and few broadleaf weeds.

4.3. Weed Density and Biomass and Crop Yields

The yield of okra under increased duration of weed infestation ranged from 463 to 2241 kg ha⁻¹ while that under increasing length of weed-free conditions showed a higher range for yield from 914 to 2360 kg ha⁻¹. The pattern was similar for soybean and maize. Increased duration of weed infestation under weed-infested treatments was associated with lower weed densities, greater weed biomass and greater yield reductions in all crops. However okra, unlike maize and soybean, exhibited greater range of weed densities and biomass particularly at both 3 and 7 weeks of weed infestation or weed-free conditions. Singh *et al.* [21] reported

susceptibility of okra to early weed infestation owing to its slow juvenile growth.

Under increased length of the weed-free period, there was also tendency for lower weed densities and weed biomass but greater yields. These results show that weed populations allowed to grow with the crop at emergence are more aggressive in terms of overall yield reduction than those that establish later in the season. Weiner *et al.* [9] and Nichols *et al.* [22] described weed suppression by crops as arising from size-asymmetric competition in which the larger crop plants suppress the initially smaller weed plants.

Radosevich and Holt [23] reported that the higher the weed density and coexistence, the greater the competition amongst weeds and between weeds and crops, which increases plant mortality particularly amongst weeds themselves leading to their lower density. Weed density may therefore not be a singular proxy to describe the responses of crops yield to weeds. Together with weed biomass however, the two indices can be used to identify competitive genotypes that have the ability to better access light, nutrients, and water resources in limited space, thus suppressing the growth and reproduction of nearby weed species [11].

Perhaps what is critical is the demonstrated potential for increased weed suppression by crops through a combination of increased crop density and spatial uniformity crop density, and/or spatial arrangement [22]. In non-water limiting conditions field studies have shown utilizing crop densities higher than 4 plants m^{-2} in maize has been shown to lower weed densities and increase yields [24]. In this study, maize was grown at inter- and intra-row spacing of 0.90 m and 0.25 m, respectively, thus giving a similar crop density and yet provided weed densities that substantially reduced yields by two thirds of weed-free control. Elsewhere in the region, maize is grown at reduced inter-row spacing of 0.75 m and intra-row spacing of 25 m [25]. Nichols *et al.* [22] reported that although many studies confirm that reducing crop row spacing reduces weeds, the effectiveness of reduced row spacing on weed control depends on several other factors, including water limitations, nutrient placement, crop to weed height ratio, crop versus weed emergence timing, and tractor-tyre spacing in mechanized systems.

Further, the relationships between weed biomass and crop yield were linear shape in all cases with R^2 being 0.75 or higher with exception of the weed-free treatment under okra. In like manner to the current study, [26] showed that yield reduction in maize due to competition from weeds was almost linearly related to the biomass of weeds growing in association with the maize. The slopes of linear regression, under weedy regime and weed-free period were greater for maize showing greater sensitivity to weeds compared to the other crops. Conversely, soybean yield showed less sensitivity to weed pressure compared to maize and okra on account of lower regression coefficient. According to [27], a competitive crop can be defined either as one that maintains a stable yield in the presence of other plants (tolerant of competition), or as one that is able to reduce plant growth effectively (able to suppress competitors). Soybean showed

the former trait with an additional observation where the range of weed biomass in soybean was similar between weed-infested treatments and weed-free treatments and the converse was evident in okra and maize, respectively.

4.4. Critical Period of Weed Control and Crop Yields

The study identified the crossing point of the critical weed-free period and the critical period of weed infestation which is defined as the equality point of control and interference. In fact, according to [12], this point determines the equality of increasing or decreasing crop yield in response to competitive conditions. The three crops did not exhibit similar equality points showing that they had dissimilar responses to weed interference durations.

In South Africa, [26] calculated that smallholder farmers could lose up to 55% of their crop when weeding in maize is delayed until 40 days after emergence. This is consistent with the equality point vis-a-vis critical period for weed removal of 40 days identified herein for maize. Racjan and Swanton [28] reported various works which show that the critical period for maize ranges between 1 to 8 weeks after crop emergence. For soybean, a critical period of 43 days in this study was within a window for weed removal of 26-63 days after emergence established using crop growth stages [29]. The longer critical period for weed control for soybean suggests that early and dense closure of crop canopy decreased sensitivity of yield to weed interference. Van Heemst [30] ranked different crops according to their competitiveness with respect to uncontrolled weeds. Soybean was ranked higher than maize in competitiveness against weeds. These results and ours show that soybean may be suitable for use in intentionally designed crop rotations systems to augment weed control practices. A critical period of 36 days determined for okra showed that the crop exhibited early sensitivity to weed infestation in tandem with earlier work which reported 2-4 weeks after sowing as the critical period for weed removal in okra production [31].

Although the findings are consistent with earlier work, other researchers [29, 32] have argued that expressing data as days after planting could indicate more variation between locations and years due to different planting dates and different environments. It is suggested that the critical period of weed control should be determined using crop growth stages and/or heat units to account for environmental variation.

5. Conclusion

The weed species *Oxalis latifolia*, *Cyperus esculentus*, *Amaranthus hybridus*, *Ipomoea purpurea* and *Nicandra physaloides* occurred throughout the different weed-infested and weed-free interference durations. These species exhibited extensive ecological need with ability to grow in different spatial and temporal niches. The similarity matrix based on Jaccard's coefficient showed that the composition of weeds under weed-free treatments in soybean was not identical to that of maize and okra, respectively. Further, the weed flora

was not homogenous under different lengths of weed-free period showing the combined influence of weed removal and crop on the composition of weed infestation.

There were no significant differences in the prevalence of weeds with either C₃ or C₄ photosynthetic pathways amongst the three crops under either increasing duration of weed infestation or increasing length of weed free period. The work however demonstrated merit in incorporating biological knowledge of weed-crop interactions through indicating trajectories of carbon fixation pathways as a prelude to determining management programmes for weeds. A longer critical period for weed control and lower regression coefficient between weed biomass and yield for soybean, compared to maize and okra, suggested decreased sensitivity of the crop to weed interference.

If advice is to be generated for farmers on how to achieve a competitive crop, the likely variability in composition and life history traits of weeds should be known. In order to check the consistency of findings in this work, further studies should be carried out with different crops and cultivars in several sites and seasons.

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