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Economic Importance of Managing Spatially Heterogeneous Weed Populations[1]

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Abstract: Three methods of predicting the impact of weed interference on crop yield and expected economic return were compared to evaluate the economic importance of weed spatial heterogeneity. Density of three weed species was obtained using a grid sampling scheme in 11 corn and 11 soybean fields. Crop yield loss was predicted assuming densities were homogeneous, aggregated following a negative binomial with known population mean and k, or aggregated with weed densities spatially mapped. Predicted crop loss was lowest and expected returns highest when spatial location of weed density was utilized to decide whether control was justified. Location-specific weed management resulted in economic gain as well as a reduction in the quantity of herbicide applied.

Nomenclature: Corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.

Additional index words: Competition, negative binomial, patch, corn, sampling, precision agriculture, integrated pest management, *Abutilon theophrasti,* ABUTH, *Setaria* spp., *Amaranthus* spp.

Abbreviations: *ER,* economic return; *ET,* single year economic threshold; X_{eq}, density equivalent; *YL,* yield loss; YL_c, yield loss based on weed density within a cell; YL_k, yield loss based on mean weed density adjusted for the distribution of weed density within that field; YL_x, yield loss based on mean weed density for the entire field.

INTRODUCTION

Predicting crop yield loss due to weed competition is a critical component of dynamic decision making for integrated weed management. Accurate prediction of crop loss requires an assessment of the weed population. A population of weeds in a grower's field may be regarded in three ways: (1) as a homogeneous unit, (2) known to vary in density but without information as to the spatial location of a specific density (i.e., frequency distribution of weed density within subunits of the field is known), or (3) weed density within each subunit of the field is spatially mapped. The goal of this research was to explore the importance of these three views on predicted crop yield loss and expected economic return.

An empirical model for predicting crop yield loss (*YL*) as a function of measured weed density (Cousens 1985) has become a standard component of crop–weed interference research:

$$YL_x = \frac{acx}{1 + cx} \qquad [1]$$

where x is mean weed density for the whole field, a represents YL_x as $x \to \infty$, and c is the ratio of the initial slope of the function ($I = dYL_x/dx$ as $x \to 0$) to a (Brain and Cousens 1990). A method of incorporating multispecies weed densities into equation 1 has been utilized for a few weed species (Swinton et al. 1994). However, estimation of the a and c coefficients using this method requires data from multispecies weed–crop interference research, which is not currently available for most species mixtures.

Assuming an additive effect of all weed species on crop yield reduction, Berti and Zanin (1994) proposed a method to predict crop yield loss from multispecies weed infestations by transforming mean density of each species into a density equivalent (X_{eq}). This method adjusts actual mean weed density based upon the relative competitive effect of each species on crop yield. To obtain density equivalent, a hypothetical weed species with arbitrarily set values of the a and c coefficients (redefined as A_{eq} and C_{eq}) is defined. Crop yield loss is therefore redefined as:

$$YL_{x,eq} = \frac{A_{eq}C_{eq}X_{eq}}{(1 + C_{eq}X_{eq})} \qquad [2]$$

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where X_{eq} is the density equivalent. Setting equation 1 equal to equation 2 and isolating X_{eq} yields:

$$X_{eq} = \frac{acx}{A_{eq}C_{eq} + C_{eq}cx(A_{eq} - a)} \qquad [3]$$

Density equivalent is therefore obtained for any weed species based upon species-specific values of *a, c,* and *x.* The benefit of this method is that density equivalents are additive and a single equation can be used to describe the impact of all species present in the mixture:

$$YL_{x,t} = \frac{A_{eq}C_{eq}\sum_{i=1}^{t} X_{eq,i}}{(1 + C_{eq}\sum_{i=1}^{t} X_{eq,i})} \qquad [4]$$

where A_{eq} and C_{eq} are analogous to *a* and *c* in equation 1 but are constant for all $X_{eq,i}$; the subscript *i* is a species identifier; and *t* is the total number of species present.

The *a* and *c* coefficients in equations 1 and 3 are based on small plot weed–crop interference data with homogeneous weed densities. On a field scale, however, weed densities are not spatially homogeneous (Johnson et al. 1995b; Navas 1991; Thornton et al. 1990; van Groenendael 1988; Wiles et al. 1992). Field-scale mean weed density estimates may therefore be irrelevant considering the spatial diversity and density of weed populations across large areas. Use of field-scale mean density estimates in spatially heterogeneous weed populations results in underprediction of yield loss at locations where weed density is high, and overprediction in parts of the field where densities are low or weeds are absent. The net result of ignoring spatial heterogeneity is an overprediction of whole field yield loss (Auld and Tisdell 1988; Brain and Cousens 1990; Nordbo and Christensen 1995). Spatial variation in weed density must therefore be accounted for to accurately predict crop yield loss.

Intensive sampling can be used to determine the frequency distribution and spatial location of weed densities within fields (Johnson *et al.* 1995b). Under an intensive sampling scheme, a grid system is imposed on a field and weed counts are made at each intersection of the grid, resulting in a discrete number of cells (*d*) per unit field area. Weed population density within each cell is commonly assumed to be homogeneous. Grid-sampled data may be used to: (1) fit a frequency distribution equation to describe the proportion of cells having a given weed density, or (2) produce a spatial map of weed density within all cells.

If a frequency distribution equation consistently fits weed count data, then its probability density function may be used to adjust the yield loss equation. Johnson *et al.* (1995b) found that the negative binomial distribution consistently fit weed seedling count data for multiple species, locations, and years. Assuming the negative binomial distribution, Brain and Cousens (1990) developed an expanded version of equation 1:

$$YL_k = a\int_0^1 xz^{1/c}\left(\frac{k}{k + x(1 - z)}\right)^{k+1} dz \qquad [5]$$

where *a, c,* and *x* are defined as above; *z* is a component of the probability density function (Brain and Cousens 1990); and *k* is an estimated parameter of the negative binomial that describes the variance at a given mean value. The *k* parameter has been used to describe spatial aggregation such that, at constant mean, decreasing values of *k* are associated with a greater proportion of cells having zero or low weed density. Since equation 5 was derived from equation 1, it may be expanded to include the influence of multiple weed species using A_{eq}, C_{eq}, k_i, and density equivalent ($X_{eq,i}$) for each species:

$$YL_{k,t} = A_{eq}\sum_{i=1}^{t}\int_0^1 X_{eq,i}z^{1/C_{eq}}\left(\frac{k_i}{k_i + X_{eq,i}(1 - z)}\right)^{k_i+1} dz \qquad [6]$$

where the subscript *i* is a species identifier and *t* is the total number of species in a field. Brain and Cousens (1990) found that yield loss predicted from equation 1 was greater than that predicted from equation 5 using hypothetical estimates of *k* and *x,* but the magnitude of the differences were dependent upon the actual values of *k* and *x.* In this research, estimates of *k* and *x* for a number of weed species in several farm fields (Johnson *et al.* 1995b; Wyse-Pester 1996) will be used to compare yield loss as predicted from equations 4 and 6.

Maps of weed density produced from grid sampling may be used to predict field-scale yield loss by averaging yield loss predicted within each cell:

$$YL_{c,t} = \frac{\sum_{i=1}^{d} YL_{x,j}}{d} \qquad [7]$$

where $YL_{x,j}$ is predicted using equation 4 for each cell (*j*) and *d* is the total number of cells within the field. If the size of a cell on the sampling grid is on a scale at which field manipulations take place (e.g., the width of a spray boom), then a spatial map of weed densities within each cell may be used to direct management de-

Table 1. Single species a and c values used to calculate predicted yield loss, economic threshold weed density equivalents calculated using equation 8 with $I = dYL/dX_{x,eq}$ at $X_{x,eq} = 0$ ($ET_{x,eq}$) or $I = dYL/dX_{k,eq}$ at $X_{k,eq}$ at $X_{k,eq} = 0$ ($ET_{k,eq}$), and actual weed density required to achieve the threshold density equivalent (assuming single species weed stands).

Crop	Weed	a	c	Source	$ET_{x,eq}$	$ET_{k,eq}$	X_x	X_k
					Plants m^{-1} row			
Corn	Velvetleaf	0.789	0.1518	Lindquist et al. 1996	0.167	0.277	0.63	0.87
	Foxtail	0.191	0.0603	Staniforth and Weber 1956	0.167	0.277	9.46	15.33
	Pigweed	0.516	0.2771	Knezevic et al. 1994	0.167	0.277	0.56	0.78
Soybean	Velvetleaf	0.719	0.3491	Lindquist et al. 1995	0.224	0.372	0.41	0.70
	Foxtail	0.168	0.0314	Kanke and Slife 1962	0.224	0.372	37.32	167.40
	Pigweed	0.454	0.2401	Dieleman et al. 1995	0.224	0.372	1.04	1.88

cisions within that cell. For example, if weed density within a cell exceeds an economic threshold density equivalent, then a grower may choose to apply an herbicide within that cell. This site-specific approach to weed management is intuitively the most cost-effective and aids in the reduction of herbicide use (Johnson et al. 1995b; Wallinga 1995).

The objective of this research was to compare predicted yield loss and expected economic return from corn and soybean under the assumption of a homogeneous weed population, an aggregated population following the negative binomial, or aggregated with weed densities spatially mapped within each cell.

MATERIALS AND METHODS

Sampling Procedure and Analyses. Weed seedling populations were sampled in 11 corn and 11 soybean fields from 1992 to 1995. Spring tillage and preemergence weed control were used according to the needs perceived by the individual farmer. Preemergence herbicide applications were applied in a 30-cm band centered over the crop row. A 7- by 7-m grid coordinate system was established on about 4 ha in each field. Approximately 800 X, Y intersection points were sampled within a field. Weed seedling density per species was assessed prior to cultivation or postemergence herbicide application in a 0.76-m^2 (1 by 0.76 m) frame centered between crop rows at each grid intersection (Johnson *et al.* 1995a; Wyse-Pester 1996). Weed densities counted within a frame are considered representative of density within the 7- by 7-m cell.

Johnson *et al.* (1995b) fit the negative binomial distribution to observed frequencies of individual weed species count data and reported mean weed density (x) and maximum likelihood estimates of k for each species in 16 fields sampled in 1992 and 1993. The same procedure was followed to obtain mean weed density and k estimates for data collected within six fields in 1994 and 1995 (Wyse-Pester 1996).

Economic Importance of Spatial Heterogeneity. The importance of spatial heterogeneity in weed density on predicted crop yield loss caused by interference from each of three weed species was assessed. Weeds selected for study were velvetleaf (*Abutilon theophrasti* Medik.), pigweed species (*Amaranthus retroflexus* L. and *A. rudis* Sauer), and foxtail species [*Setaria faberii* Herrm. and *S. glauca* (L.) Beauv.]. Species of both pigweed and foxtail were pooled for density counts because of difficulties in distinguishing them at the cotyledon and first leaf stage. These species were selected for analysis because they were the most commonly occurring weeds in the 22 fields sampled. Yield loss resulting from interference by all species present in each field was predicted using equations 4, 6, and 7. Values of a and c used to predict the effect of each species on corn and soybean were obtained from experiments conducted within the central Corn Belt of the United States and Canada (Table 1). A hypothetical weed species was defined by setting A_{eq} and C_{eq} to constant values of 0.9 and 0.5, respectively, for both corn and soybean. These constants, the species-specific values of a and c, and observed weed density counts (Table 2) were then used to calculate density equivalent (equation 3) for each weed species in each field (Table 3). This approach facilitates the direct comparison of yield loss predictions using equations 4, 6, and 7.

Importance of weed spatial heterogeneity was evaluated by calculating and comparing expected economic returns under three hypothetical herbicide use decision rule scenarios. Under each decision rule scenario, a generic herbicide was applied if the weed density within a specified area exceeded a single year economic threshold density (see Cousens 1987 for a discussion of economic thresholds). The three scenarios differed in the total area sprayed and the method of calculating and using the economic threshold.

Single year economic threshold was calculated (Marra and Carlson 1983):

$$ET = \frac{H}{Y_{wf}PE_fI} \qquad [8]$$

Table 2. Mean density (x) and aggregation parameter (k) values for velvetleaf (v), foxtail spp. (f), and pigweed spp. (p) in 22 fields.

Field[a]	Crop	x_v	x_f	x_p	k_v	k_f	k_p
		Seedlings m^{-1} row					
1	Corn	0.38	0.58	0.54	0.09	0.1	0.12
3	Corn	1.70	—	—	0.53	—	—
4	Corn	6.51	—	0.08	0.73	—	0.10
5	Corn	2.18	—	0.09	0.59	—	0.23
7	Corn	—	—	0.17	—	—	0.03
8	Soybean	8.18	0.04	0.09	0.24	0.01	0.12
9	Soybean	15.4	—	1.89	1.65	—	0.55
10	Soybean	0.85	8.31	—	0.30	0.35	—
11	Soybean	0.04	0.33	—	0.02	0.03	—
12	Soybean	0.18	0.11	—	0.01	0.12	—
13	Corn	0.03	0.08	0.04	0.02	0.05	0.03
14	Corn	0.08	0.04	0.41	0.04	0.01	0.09
15	Corn	1.2	0.97	—	0.28	0.24	—
16	Soybean	0.08	—	—	0.01	—	—
17	Soybean	0.31	0.41	0.60	0.13	0.13	0.14
18	Soybean	1.95	1.37	0.83	0.34	0.27	0.04
(1)	Corn	1.50	—	—	0.64	—	—
(2)	Soybean	5.24	—	—	0.19	—	—
(3)	Corn	0.05	—	—	0.01	—	—
(3)	Soybean	0.06	2.68	—	0.02	0.11	—
(4)	Corn	0.48	—	—	0.03	—	—
(4)	Soybean	0.16	0.18	—	0.01	0.07	—

[a] Field numbers in parentheses are those in Wyse-Pester (1996); all others are those in Johnson et al. (1995b).

Table 3. Expected economic returns (ER) under the three decision rule scenarios for all species present in 22 fields. Expected returns in the absence of any weeds were \$220.68 ha^{-1} and \$81.52 ha^{-1} for corn and soybean, respectively.

Crop	Field[a]	$X_{eq'i}$	Decision rule scenario ER_1	ER_2	ER_3
			\$ ha^{-1}		
Corn	(3)	0.0133	216.55	218.53	219.98
	13	0.0226	213.67	216.35	217.52
	7	0.0530	204.56	212.68	217.46
	(4)	0.1266	183.47	206.02	217.68
	14	0.1466	178.02	197.00	209.26
	(1)	0.3883	164.18	187.78	199.25
	1	0.2761	166.76	175.93	199.19
	15	0.3361	165.35	168.92	194.88
	3	0.4385	163.10	167.26	187.91
	5	0.5858	160.18	165.12	180.74
	4	1.5696	146.86	155.91	162.54
Soybean	11	0.0260	75.52	78.17	79.53
	16	0.0444	71.42	77.72	80.04
	(3)	0.0649	66.87	73.53	80.91
	(4)	0.0904	61.33	75.54	79.26
	12	0.1004	59.25	75.31	79.52
	17	0.3097	28.93	43.97	64.34
	10	0.5278	25.45	29.12	52.44
	18	1.1552	18.12	25.00	46.47
	(2)	2.1367	11.12	24.63	52.59
	8	2.9203	7.53	21.64	40.15
	9	4.5010	2.93	5.10	7.23

[a] Field numbers in parentheses are those in Wyse-Pester (1996); all others are those in Johnson et al. (1995b).

where H is cost of the herbicide and its application, Y_{wf} is weed-free crop yield, P is price obtained for the crop, E_f is herbicide efficacy, and I is the initial slope of the yield loss function ($I = dYL/dX_{eq}$, at $X_{eq} = 0$). Calculation of I will vary depending on the equation used to calculate YL. For $YL_{x,t}$ (equation 4):

$$I = A_{eq}\,C_{eq}$$

and for $YL_{k,t}$ (equation 6):

$$I = A_{eq} \int_0^1 (Z^{(1/C_{eq})})\,dz$$

where z was integrated over values ranging from 0 to 1 using a step size (dz) of 0.001. For simplicity, it was assumed that a single herbicide could be applied in both corn and soybean and was equally effective on all three weed species. Economic return was calculated using:

$$ER = Y_{wf}\,P(1 - YL(1 - 0.9q)) - C - Hq \quad [9]$$

where C is the cost of crop production and q is a binary term equal to zero if no herbicide was applied and 1 if it was applied. The value of 0.9 is a yield loss reduction factor used if the herbicide was applied. Values for H, Y_{wf}, P, E_f, and C for corn and soybean were obtained from Lindquist et al. (1995). While it is unlikely that weed-free yield, herbicide efficacy, or production cost would be constant across fields or farms, they were held constant. Moreover, because the cost of weed sampling is unknown and the cost of the global positioning system required to implement intermittent spray technology is constantly changing, these costs were not incorporated into equation 9.

Under the first decision rule scenario, economic threshold ($ET_{x,eq}$) was calculated using predicted crop loss under the assumption of a spatially homogeneous weed population (equation 4). Herbicide was applied to the entire field only if the density equivalent for that field exceeded $ET_{x,eq}$. Expected economic return was calculated using equation 9. This first decision rule scenario simulates threshold-based herbicide use commonly utilized in currently available weed management decision aid models (Mortensen et al. 1995; Wilkerson et al. 1991).

Under the second decision rule scenario, yield loss predictions from equation 6 were used to obtain a single year economic threshold ($ET_{k,eq}$). Herbicide was applied over the entire field only if the density equivalent exceeded this threshold. Comparison of expected return using scenarios 1 and 2 will provide information on the potential costs/benefits of utilizing the frequency distribution of weed density within cells to decide when to use a broadcast herbicide application.

Under the third decision rule scenario, a single year economic threshold was calculated using predicted yield loss from equation 4 ($ET_{x,eq}$). If density equivalent within

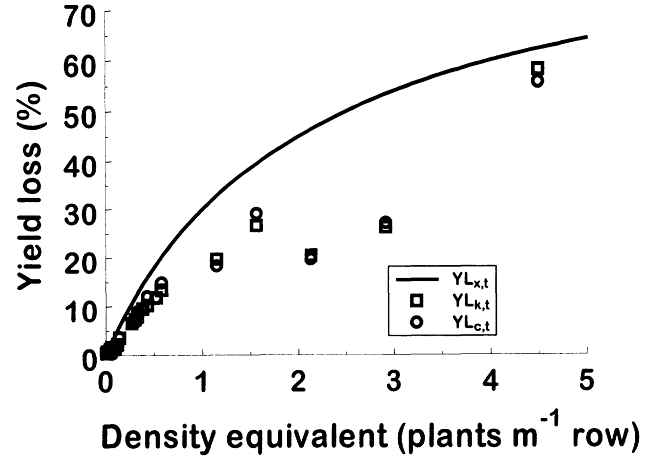

Figure 1. Predicted crop yield loss using equations 4 ($YL_{x,t}$), 6 ($YL_{k,t}$), and 7 ($YL_{c,t}$).

a cell exceeded this threshold, then the area within that cell (7 by 7 m) was sprayed. If the threshold was not exceeded, no herbicide was applied within the cell. Expected economic return was then calculated for each cell and summed across all cells within a field. Comparison of expected returns obtained using scenarios 1, 2, and 3 will yield insight into the potential benefits of utilizing site-specific weed density to apply herbicide only where needed.

RESULTS AND DISCUSSION

Predicted yield loss was consistently higher when weeds were assumed to be homogeneously distributed across the field ($YL_{x,t}$, equation 4) than when density distribution information ($YL_{k,t}$ or $YL_{c,t}$) was used (Figure 1). This difference was greater at moderately high weed densities and for lower k values, agreeing with the predictions of Brain and Cousens (1990). Yield loss predictions obtained from equation 6 ($YL_{k,t}$) did not differ consistently from yield loss calculated on a cell by cell basis ($YL_{c,t}$, equation 7, Figure 1), suggesting that if mean weed density (x) and the aggregation parameter (k) are known, an accurate estimate of field-scale crop yield loss may be obtained using equation 6. Johnson *et al.* (1995b) showed that k was positively correlated with observed mean weed density across fields and suggested the value of k for any given species may be a stable field-specific characteristic. Wyse-Pester (1996) found in a 4-year study that k was stable across years within four fields. Wilson and Brain (1991) also suggested that weed distribution may be stable over the long term. Assuming k is stable, intensive sampling would only be required periodically. Annual costs of sampling in subsequent years would be reduced because mean weed density may be estimated with minimum sampling effort using sequential sampling methods (Johnson *et al.* 1995b).

Brain and Cousens (1990) compared yield loss as predicted from equations 1 and 5 using hypothetical values of x and k and showed that differences were small at low mean weed density and small values of c (i.e., low X_{eq}). Assuming that mean weed density will be maintained at low levels in well-managed fields, they questioned the utility of obtaining and using weed density frequency distribution for practicing growers. While results shown in Figure 1 also show apparently small differences in yield loss at low X_{eq}, differences in economic return between scenarios 1 and 3 exceeded \$10/ha at X_{eq} values as low as 0.05 (Table 3). All X_{eq} values in Table 3 were obtained from actual density counts made on commercial farms.

Single year economic threshold estimates calculated under the assumption of homogeneous weed populations ($ET_{x,eq}$) were smaller than those calculated assuming an aggregated population following the negative binomial ($ET_{k,eq}$, Table 1). This suggests that decisions made under the assumption of homogeneous weed populations may result in herbicide application when it is not necessary. Use of $ET_{k,eq}$ to make broadcast herbicide application decisions may therefore be beneficial for reducing long-term herbicide application. However, several researchers have shown that the proportion of a field requiring herbicide application is considerably less when weed populations are spatially aggregated (Johnson *et al.* 1995b; Mortensen *et al.* 1995; Wallinga 1995; Wiles *et al.* 1992). While use of $ET_{k,eq}$ may reduce the frequency of herbicide application, a substantial portion of the field will receive herbicide even in locations where it is not needed. To reduce herbicide use and the cost associated with it, intermittent spray technology may be coupled with spatial weed maps to spray only those portions of the field where weed density exceeds the threshold level (Johnson *et al.* 1995b; Mortensen et al. 1998).

The approach presented utilizes single year economic threshold levels of weeds to direct postemergence weed control decisions. Concern over seed production by uncontrolled weeds led Wallinga (1995) to use a zero-threshold level in determining the proportion of a field requiring herbicide application. Alternatively, a multiyear economic optimum threshold approach may be utilized to direct decision making (Bauer and Mortensen 1992; Cousens 1987; Lindquist *et al.* 1995).

This approach, however, requires an understanding of the long-term population dynamics of the weed. Dynamics of the formation, spread, and interaction among weed patches need to be accounted for in such an analysis (Maxwell and Colliver 1995).

Expected economic returns were consistently higher when single year economic thresholds ($ET_{x,eq}$) were used to make site-specific (within a cell) herbicide application decisions (scenario 3), particularly when weed density was high or the weed was highly competitive with the crop (Table 3). Difference in economic return that constitutes a significant improvement among scenarios is not currently known because the cost of obtaining weed spatial heterogeneity information is not known. Since mapping and intermittent spray technology is in a stage of rapid evolution, their cost may decrease sufficiently in the near future to justify their use in making herbicide application decisions. A midwestern U.S. farmer recently invested $6,000 on a global positioning system and on-board computer designed to change seeding rate on the go based on a spatial map of soil characteristics (Sickman 1995). Assuming (1) a similar cost for intermittent spray equipment, (2) equipment will be outdated after 6 yr of use, and (3) farm size is 200 ha, this translates to a cost of $5 ha. Add $5/ha as a possible cost of obtaining the spatial map and the total cost of utilizing this technology is $10/ha. Results indicate that the technology becomes profitable (under scenario 3) at an X_{eq} of about 0.06. At higher X_{eq}, use of weed density frequency distribution (equation 6 to calculate $ET_{k,eq}$) and a spatial map of weed density to direct herbicide application improved expected economic returns by up to $18.98 and $37.17/ha, respectively (Table 3). In a similar study, Maxwell and Colliver (1995) suggested that site-specific control of *Avena fatua* L. in spring wheat resulted in a gain of up to $17.18 ha^{-1} over the practice of broadcast applying an herbicide under the assumption of homogeneous weed populations.

Site-specific weed management may result in economic gain as well as a reduction in the quantity of herbicide applied. The economic advantage of this approach results from the reduction in herbicide cost (Maxwell and Colliver 1995). Reduction of applied herbicide fits well within the goals of an integrated weed management program. Further gains may be made by increasing the economic threshold level of weeds. This may be accomplished by incorporating any management practice that reduces the competitive influence of the weed on crop yield or the long-term population growth of the weed.

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