Rational Suppression of Sunflower Rust: Development and Evaluation of an Action Threshold

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ABSTRACT

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The efficacy of one protectant (maneb) and six systemic fungicides in the suppression of sunflower rust caused by *Puccinia helianthi* was evaluated in one set of three field trials conducted during 1992. Cyproconazole, hexaconazole, and tebuconazole were highly effective in controlling rust, whereas maneb, fenbuconazole, difenoconazole, and promoconazole were only partially effective. In another set of three field trials during 1992, the injury threshold, i.e., the level of disease intensity at which fungicide should be applied to achieve adequate disease suppression, was found to be an average rust severity of 3%, on the upper four leaves. The relationship between the time at which disease reached the injury threshold and the resulting damage to yield was linear and negative. When the injury threshold was reached at or later than 27 days after flowering, the resulting damage was insignificant. Consequently, the action threshold for management of sunflower rust was defined as the occurrence of disease severity of 3% prior to the 27th day after flowering. The developed action threshold was examined in two field trials during 1993 in which spraying was or was not carried out in accordance with the developed action threshold. Predictions of outcome, based on the developed action threshold, were accurate in all cases.

Puccinia helianthi Schwein., the causal agent of rust in sunflower (*Helianthus annuus* L.), endangers sunflower production wherever this crop is cultivated extensively. Rust severity varies with the environment, age of the host, and inherent resistance of the host species and cultivar. When infestation is severe, leaves senesce prematurely and yields may be reduced to as little as 15% of the attainable yield (3,8,9,16–18). Rust reduces not only yield, but also oil percentage, seed size, test weight, and kernel-to-hull ratio (11). The most effective way to avoid losses from rust is by planting rust-resistant hybrids. Rust resistance in sunflower is race-specific. Currently there are at least five races of rust. The predominant race may change from year to year and may also vary by location. For example, in a survey conducted by Rashid (12) in the Canadian prairies during 1988–1990, race 4 predominated in 1988, followed by race 3, whereas race 3 predominated in 1989 and 1990, followed by races 1 and 4. Most oilseed hybrids have good resistance to race 3. No hybrids are resistant to race 4, and none is resistant to all races.

In general, hybrids and cultivars grown for consumption are more susceptible to rust than are those grown for oilseed (6). To minimize the risks of losses in susceptible hybrids, one can employ management practices that include destruction of volunteers and avoidance of high rates of nitrogen fertilizer and high plant populations (10). Because of the relatively low net value of oilseed sunflower, fungicides are considered as a last resort for rust control in these hybrids. However, the situation is somewhat different in the case of sunflower cultivars grown for consumption, where the higher value of the yield may justify the use of chemical means to control rust, at least in some instances.

In his thoroughgoing review of the factors to be considered in the development of a rational disease management program, Zadoks (21) introduced the threshold theory and defined the terms injury, damage, and loss. Injury is any visible and measurable symptom caused by a harmful organism; damage is any reduction in the quantity and/or quality of yield; and loss is the reduction in financial return per unit area due to harmful organisms. Zadoks (21) indicated that rational disease management should be related to the pathogen's population and potential damage, and he developed the terms injury threshold, damage threshold, and action threshold. In the present study, we follow Zadoks's analysis but use slightly different definitions: An injury threshold is the level of disease at which fungicide should be applied to achieve adequate disease suppression; a damage threshold is the lowest level of disease that induces yield reductions, and an action threshold is the level of disease at which action should be taken to prevent the disease from exceeding the damage threshold.

Not much is known concerning these thresholds for the rust-sunflower pathosystem. Most of the published studies on chemical control have concentrated on evaluating the efficacy of fungicides (1,4,9,19,20). Accordingly, Gulya et al (7) indicated in an extension bulletin that "deciding at what point it is economically feasible to spray sunflower for rust control is difficult at best." They suggested that growers consider fungicide application when rust severity on lower leaves at or before flowering is 5%. A recent study (16) provided additional information on the efficacy and profitability of rust management. Adequate and cost-effective disease control was achieved by application of the fungicide tebuconazole at a rate of 0.125 kg a.i./ha when disease severity on the upper four leaves was 3%. However, the stage of crop growth at the time of application was not considered, nor was the possible use of other fungicides for disease management.

The purposes of this study were to examine the efficacy of various fungicides in rust control and to develop and evaluate an action threshold for rational suppression of the disease. A preliminary report, including a portion of the results, has been published elsewhere (15).

MATERIALS AND METHODS

Cultural practices. Eight field trials were conducted in the Lakhish, northern Negev, and coastal plain regions of Israel in 1992 and 1993. The local cultivar DY-3 was sown in all trials. This cultivar is grown for human consumption (achenes are mostly sold unpeeled) and is highly susceptible to *P. helianthi.* Seed was sown in the last week of March each year; plants were spaced 0.4 m apart within rows and 1 m between rows. The crop was irrigated via a drip irrigation system and was grown according to the cultural practices recommended for sunflower in these regions, but fungicides and insecticides were not applied. The experiments were laid out in a randomized block design with four replicates. The size of each experimental plot was 6 × 12 m. Fungicides were applied via a motorized backpack sprayer fitted with cone-jet ×6 nozzles and delivering 240–270 L/ha of water at a pressure of 275 kPa. After plants had reached maturity, the four inner rows of each experimental plot were harvested by means of a commercial

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combine. Yields were weighed and expressed as metric tons per hectare (t/ha).

Evaluation of fungicide efficacy. The efficacy of various fungicides in suppressing sunflower rust was evaluated in 1992 in a set of three field trials conducted in the Lakhish (trial 1), northern Negev (trial 2), and coastal plain (trial 3) regions of Israel. In each trial (unless otherwise indicated) the following treatments were given: 1) no treatment (control); 2) maneb (Manebgan, 2.0 kg a.i./ha, Agan, Israel), not in trial 1; 3) fenbuconazole (Indar, 0.05 kg a.i./ha, Rohm & Haas, France); 4) difenoconazole (Score, 0.125 kg a.i./ha, Ciba-Geigy AG, Switzerland); 5) promoconazole (Granit, 0.1 kg a.i./ha, Rhône-Poulenc, France); 6) cyproconazole (Atemi, 0.05 kg a.i./ha, Sandoz Agro AG, Switzerland); 7) hexaconazole (Anvil, 0.05 kg a.i./ha, ICI, England); and 8) tebuconazole (Folicur, 0.125 kg a.i./ha, Bayer AG, Germany) (Table 1). Sprays were applied three times in trials 1 and 3 and twice in trial 2, on the following dates: trial 1, 25 May and 1 and 10 June; trial 2, 31 May and 8 July; and trial 3, 28 May and 4 and 14 June. Flowering (i.e., 90% of plants had flowered) in the three trials occurred on 1 June, 31 May, and 4 June, respectively.

Development and evaluation of an action threshold. An additional set of three field trials (4–6) was conducted in 1992 to accumulate the data required for developing an action threshold for sunflower rust. The developed action threshold was then evaluated in 1993 in two field trials (7 and 8). Trials 4–6 were located adjacent to trials 1–3 and were organized as described above. Fungicides were applied once, twice, or three times on different dates and at various disease severities as determined on the upper four leaves. Difenoconazole (0.125 kg a.i./ha) was applied in trial 4, tebuconazole (0.125 kg a.i./ha) in trial 5, and cyproconazole (0.05 kg a.i./ha) in trial 6. Time of spraying and the corresponding disease severities are indicated in Table 2.

The developed action threshold was evaluated in 1993 in two field trials conducted in the northern Negev (trial 7) and Lakhish (trial 8) regions and designed as described above. Treatments consisted of spraying or not spraying (control) in accordance with the developed action threshold. Tebuconazole was applied in both trials at a rate of 0.125 kg a.i./ha on 15 and 27 June. Disease severities on those dates were 0.12 and 2.7%, respectively, in trial 7 and 2.8 and 11.6%, respectively, in trial 8. In both trials, flowering occurred on 28 May.

Disease assessment. In all trials, disease was assessed visually every 7–10 days starting in mid- to late May and ending at crop maturity (early to mid-July). Ten randomly selected plants located in the inner rows of each experimental plot were evaluated for disease development. On each plant, disease severity (i.e., percent leaf area with disease symptoms) on the upper four leaves was assessed with the aid of a disease assessment scale (7). The upper leaves were chosen because they are the main source of carbohydrates for the developing achenes (13). Disease estimates for each of the individual plants were averaged, and plot means were used for data analysis. Data were subjected to statistical analysis; whenever F values were significant at $P < 0.05$, treatments were compared according to Fisher's protected LSD test.

RESULTS

Evaluation of fungicide efficacy. Disease onset varied substantially among the trials conducted in 1992. It appeared early in trial 3, later in trial 2, and relatively late in trial 1. Consequently, a severe epidemic developed in trial 3, a moderate epidemic in trial 2, and a mild epidemic in trial 1. The observed efficacy of the tested fungicides in each trial was related to the intensity of the epidemic. In trial 1, all fungicides suppressed the disease significantly as compared with the untreated control, and differences among treatments were insignificant. In trials 2 and 3, there was sub-

Table 1. Effects of various fungicides on the severity of sunflower rust and harvested yields in three field trials in 1992

	Trial 1		Trial 2		Trial 3	
Fungicide and rate[x] (kg a.i./ha)	**Disease[y] (%)**	**Yield (t/ha)**	**Disease (%)**	**Yield (t/ha)**	**Disease (%)**	**Yield (t/ha)**
Untreated	73.5 a[z]	2.70 a	84.4 a	1.97 b	97.8 a	1.21 c
Maneb (2.0)	...	...	51.1 b	2.48 a	90.8 ab	1.52 bc
Fenbuconazole (0.05)	18.6 b	2.91 a	61.7 b	2.49 a	82.5 ab	1.59 bc
Difenoconazole (0.125)	25.1 b	2.89 a	58.4 b	2.55 a	78.5 b	1.56 bc
Promoconazole (0.1)	24.8 b	2.91 a	62.4 b	2.58 a	79.2 b	1.52 bc
Cyproconazole (0.05)	9.9 c	2.91 a	34.6 c	2.53 a	7.3 c	1.80 ab
Hexaconazole (0.05)	8.4 c	2.89 a	19.8 c	2.63 a	1.8 c	1.70 ab
Tebuconazole (0.125)	5.0 c	2.95 a	2.2 d	2.57 a	1.0 c	2.01 a

[x]Fungicides for trial 1 were applied on 25 May and 1 and 10 June, for trial 2 on 31 May and 8 July, and for trial 3 on 28 May and 4 and 14 June.
[y]Disease severity was evaluated on 12–17 June, 42–47 days after flowering.
[z]Numbers in columns followed by the same letters do not differ significantly ($P = 0.05$), as determined by Fisher's protected LSD test.

Table 2. Effects of the time of application and number of fungicidal sprays on the severity of sunflower rust and harvested yield in three field trials in 1992

	Time from flowering (days)				
Trial no.[w]	**−6 to −7**	**0**	**9–11**	**Disease[x] (%)**	**Yield (t/ha)**
4	...	...	...	72.6 a[y]	2.38 a
	X (0.0%)[z]	...	...	37.4 b	2.42 a
	...	X (traces)	...	31.1 b	2.53 a
	...	...	X (traces)	35.0 b	2.61 a
	X	X	...	29.5 b	2.68 a
	X	X	X	18.8 b	2.63 a
	...	X	X	16.7 b	2.39 a
5	...	...	...	81.7 a	2.11 b
	...	X (traces)	...	1.1 b	2.50 a
	...	...	X (0.1%)	0.9 b	2.63 a
	...	X	X	0.6 b	2.59 a
6	...	...	...	98.7 a	1.19 c
	X (0.3%)	...	...	60.8 bc	1.79 ab
	...	X (1.4%)	...	57.4 bc	1.80 ab
	...	...	X (10.0%)	80.4 ab	1.47 bc
	X	X	...	16.5 d	1.90 a
	X	X	X	5.4 d	2.02 a
	...	X	X	46.1 c	1.67 ab

[w]Difenoconazole was applied (0.125 kg a.i./ha) in trial 4, tebuconazole (0.125 kg a.i./ha) in trial 5, and cyproconazole (0.05 kg a.i./ha) in trial 6. Sprays were applied on 25 and 28 May (i.e., 6–7 days prior to flowering) in trials 4 and 6 and at the time of flowering on 1 June, 31 May, and 4 June and on 10, 8, and 14 June (i.e., 9–11 days after flowering) in trials 4, 5, and 6, in the same order.
[x]Disease severity was evaluated on 12–17 June, 42–47 days after flowering.
[y]Numbers in columns (for each trial) followed by the same letters do not differ significantly ($P = 0.05$), as determined by Fisher's protected LSD test.
[z]Severity of disease at the time of fungicide application is shown in parentheses.

stantial variation in efficacy of the fungicides, and they could be divided into two general groups. Maneb, fenbuconazole, difenoconazole, and promoconazole had low to moderate effects, and cyproconazole, hexaconazole, and tebuconazole had a pronounced effect on rust suppression. By the end of the season, fungicides in the first group had suppressed the disease by 23–38% (averages for the three trials) and those in the second group, by 79–96% (Table 1).

The effects of the fungicidal treatments on harvested yields were related both to disease severity in the trials and to efficacy of individual fungicides. In trial 1, where disease intensity was mild, yield was not affected by rust. In trial 2, where disease intensity was moderate, the use of fungicides resulted in a significant yield increase relative to the untreated control, but differences among fungicides were insignificant. In trial 3, where disease appeared relatively early and a severe epidemic developed, significant yield increases (28.8–39.8%) were achieved only in those plots treated by the highly effective fungicides (Table 1).

Development and evaluation of an action threshold. Effects of the time of fungicide application on rust development and the resulting yield were examined in trials 4–6. Where disease intensity was mild (trial 4) or moderate (trial 5), adequate disease suppression was achieved by all treatments. However, where disease was severe (trial 6), its suppression was significant only when spraying was initiated at early stages of the epidemic (i.e., disease severity <3%). When spraying was initiated at a higher disease severity, its effect was insignificant (Table 2).

Effects of treatments on yield in each trial were related to disease severity and time of spraying initiation. In trial 4, no treatment induced an increase in yield. In trial 5, all treatments resulted in significant yield increments relative to yields in the untreated plots, and differences among treatments were insignificant. In trial 6, all treatments initiated at disease severity <3% resulted in a significant yield increase (Table 2).

To identify the situations under which disease control is beneficial, we examined the relationship between disease intensity and the resulting damage to yield. Disease intensity was expressed as the time (measured from flowering) at which disease severity reached the injury threshold (i.e., a severity of 3% on the upper four leaves). Damage was calculated as the relative difference in yield between plots treated with tebuconazole and untreated plots. Yields obtained in plots treated with tebuconazole were considered as a good approximation of the attainable yields (i.e., yield in the absence of rust) because this fungicide was highly effective in all trials. To derive a more general conclusion from the analysis, data from a previous study (16) and from trials conducted in this study (trials 1–3) were included. The relationship between the time at which disease reached the injury threshold and the resulting damage was linear and negative. When the injury threshold was reached 31 or more days after flowering, yield was not affected by the disease (Fig. 1). Upper and lower limits of ±10% were calculated for the curve presented in Figure 1, and the lower limit, 27 days after flowering, was used as an approximation of the damage threshold for further analysis.

The developed injury and damage thresholds were then used to define the action threshold for suppression of sunflower rust. Whenever the injury threshold is reached prior to the occurrence of the damage threshold (i.e., if a disease severity of 3% is reached earlier than 27 days after flowering), significant yield damage can be expected. Accordingly, spraying will be cost-effective. Whenever the injury threshold is reached after the occurrence of the damage threshold (i.e., if a disease severity of 3% is reached later than 27 days after flowering), minor yield damage is expected and fungicide applications will not be beneficial.

The accuracy of the developed action threshold was evaluated in two field trials in 1993. In trial 7, disease developed relatively late in the season and the injury threshold was reached 32 days after flowering. According to the developed action threshold, no spraying was needed in this situation. Sprays were nevertheless applied, to test the validity of the developed action threshold. The first spray was applied 18 days after flowering at a disease severity of 0.12% (i.e., below the injury threshold). In another treatment, a spray was applied 32 days after flowering at a disease severity of 2.7% (i.e., close to the injury threshold but later than the damage threshold). Disease suppression was adequate in the first treatment and less effective in the second. However, neither treatment resulted in a significant increase in yield, indicating that spraying had actually not been needed (Fig. 2A). In trial 8, disease developed relatively early and the injury threshold was reached 18 days after flowering. A spray applied at that time (i.e., in accordance with the developed action threshold) suppressed rust development significantly throughout the entire growing season and resulted in a significant yield increase (Fig. 2B). In another treatment, a spray was applied 30 days after flowering at a disease severity of 11.6% (i.e., higher than the injury threshold and later than the damage threshold). Disease control in that treatment was insufficient and the effect on yield was insignificant (Fig. 2B).

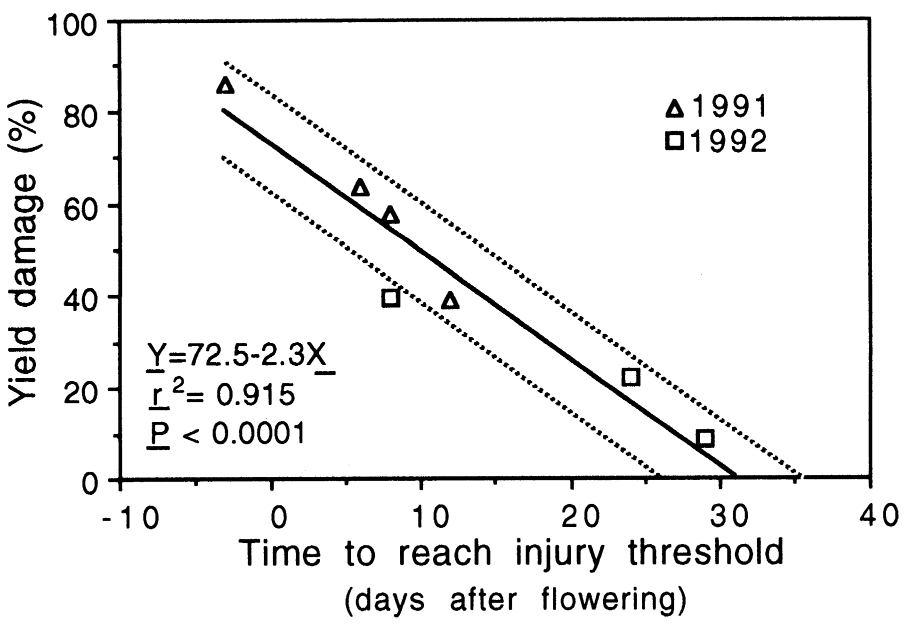

Fig. 1. Relationship between disease intensity of rust and the resulting damage to sunflower yield. Disease intensity is expressed as the time (measured from flowering) at which disease reached the injury threshold (i.e., rust severity of 3% on the upper four leaves). Analysis is based on trials conducted by Shtienberg and Zohar in 1991 (16) and on trials 1–3 conducted in 1992. The solid line represents the fitted regression equation and the dashed lines are deviations of ±10% from the regression line.

DISCUSSION

Although sunflower rust is very common in Israel, both the time of onset of the disease and its intensity vary substantially among fields. Consequently, there are some situations in which yield is reduced and fungicide spraying would be cost-effective and there are other situations in which yield is not affected and spraying would not be justified. A rational disease management program should be based on a reliable prediction of the probability that yield damage will occur. Other factors to be taken into account are the efficacy of the available fungicides and the time period during the course of the epidemic when spraying would still result in adequate disease suppression. Observations made during a 4-yr study (1991–1994) revealed that the rate of rust development is relatively constant under Israeli conditions (14). Accordingly, effects of the environment on *P. helianthi* are not considered in the decision-making procedure.

This study was conducted in four steps. First, the efficacy of various fungicides in suppressing rust was examined. Second, the highest disease severity at which spraying still resulted in adequate disease control (i.e., the injury threshold) and the situations in which rust epidemics induced yield reductions (i.e., the damage threshold) were determined. Third, the above results were integrated and an action threshold was developed. Finally, the accuracy of the developed action threshold was examined in two field trials in the subsequent growing season.

The efficacy of fungicides in suppressing sunflower rust has been evaluated in a number of studies. The fungicides examined were mostly of the protectant type, and their efficacy was usually low to moderate (1,4,5,9,19,20). Recently, the efficacy of the systemic fungicide tebuconazole was evaluated under a very severe epidemic of rust and was highly effective (16). Here we conducted a set of field trials that demonstrated the efficacy of one protectant (maneb) and six systemic fungicides in suppressing rust. Maneb was relatively ineffective. Fenbuconzole, hexaconazole and tebuconazole were highly effective, whereas fenbuconazole, difenoconazole, and promoconazole were only partially effective (Table 1). All the systemic products tested are of the triazole group of fungicides and share a similar mode of action, namely, alteration of the pathway of sterol biosynthesis in the fungus pathogen. Variations in efficacy among fungicides sharing a similar mode of action is not uncommon and could result from several factors (2), such as differences in the rate of penetration into the pathogen's organs, production of secondary toxic metabolites, differences in mobilization within the host tissue, and existence of a secondary mode of action.

The injury threshold is an expression of disease severity. Its actual value is related to efficacy of the fungicide being used; it is higher for highly effective fungicides than for moderately effective ones. For the highly effective fungicides examined in this study (tebuconazole, hexaconazole, and cyproconazole), the injury threshold was defined as a disease severity of 3%, on average, on the upper four leaves (Table 2; 16). Initiation of spraying at higher disease severities (e.g., 10%) resulted in inadequate disease suppression (Table 2). In determining the injury threshold, we considered only the efficacy of rust suppression; the cost-effectiveness of the treatment was not taken into account.

The degree of yield damage caused by a plant pathogen is the outcome of two dynamic processes occurring simultaneously: disease progress and yield accumulation. In most plant-pathogen systems the degree of yield damage is related to the time of disease appearance, i.e., the earlier the disease appears, the greater the damage. To quantify this relationship, the results obtained in 1991 (16) and 1992 (Table 2) in three growing regions were analyzed concurrently. Disease intensity was expressed in terms of the injury threshold and yield accumulation as the time passed from flowering. Analysis of the results revealed that when the injury threshold was reached 31 days after flowering or later, yield was not affected by the disease (Fig. 1). However, the damage values used in the analysis were obtained from field trials and were therefore subject to experimental error. In the development of a reliable action threshold, these error terms should be taken into account. Zadoks and Rabbinge (22) indicated that the least significant difference in yield obtained in field experiments on crop protection is rarely smaller than 5% of the yield. On the basis of our experience with the rust-sunflower pathosystem, 10% would be a more realistic estimate. Consequently, upper and lower limits of ±10% were calculated for the curve presented in Figure 1. We chose the lower limit, i.e., 27 days after flowering, as the

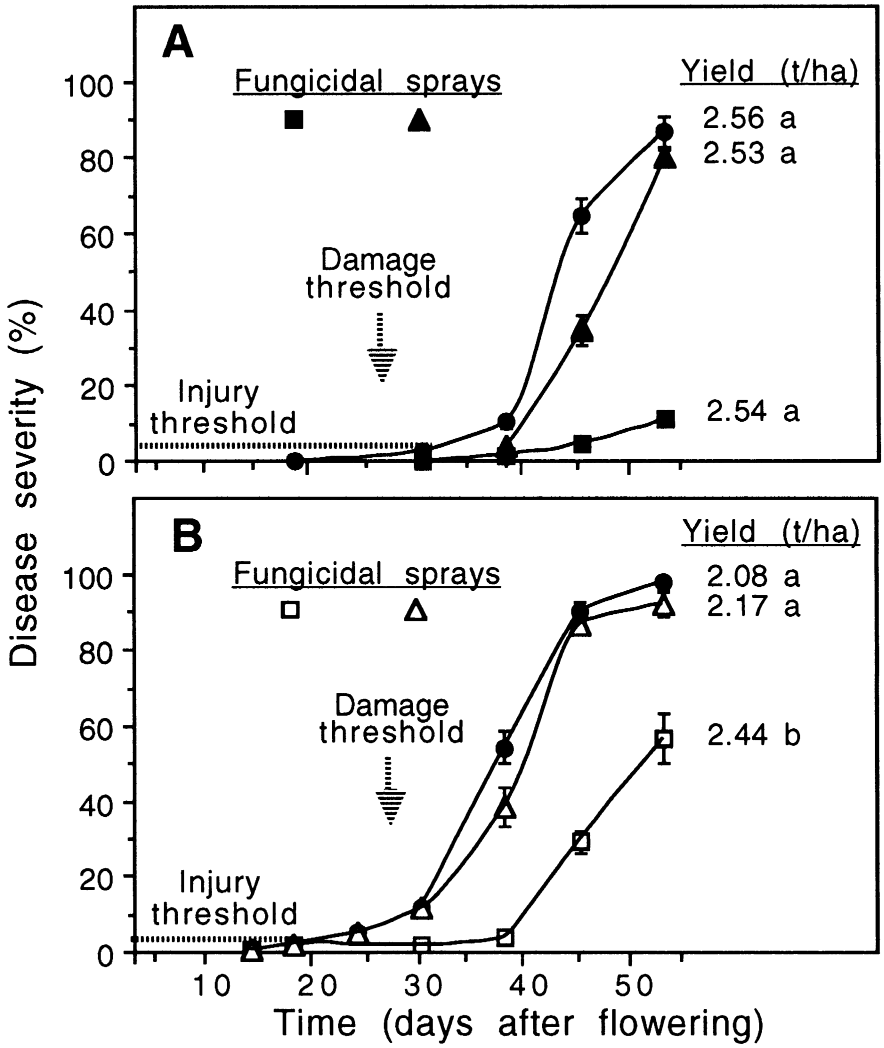

Fig. 2. Disease progress curves in two field trials—**(A)** trial 7 and **(B)** trial 8—conducted in 1993 for evaluation of the developed action threshold for sunflower rust. Vertical bars adjacent to symbols indicate the standard error. Horizontal dashed lines indicate the injury threshold (i.e., rust severity of 3% on the upper four leaves). Dashed arrows indicate the damage threshold (i.e., 27 days after flowering). Squares and triangles in the upper section of the graphs indicate the times at which fungicides were applied for the corresponding treatments. Circles indicate the control treatment. Numbers at the right of the graphs indicate the harvested yields for each treatment; numbers followed by the same letter do not differ significantly ($P = 0.05$) as determined by Fisher's protected LSD test.

damage threshold. This conservative approach was adopted because our aim was to minimize the risks of false-positive management action, i.e., application of a spray when not needed. Consequently, the action threshold for management of sunflower rust was defined as the occurrence of disease severity of 3% earlier than 27 days after flowering.

The developed action threshold was examined in two field trials in 1993. In these trials, spraying was or was not applied in accordance with the developed action threshold. Predictions of outcome were accurate in all cases (Fig. 2). We therefore conclude that the developed action threshold is accurate and reliable enough to be worth testing under commercial situations on a limited scale. During the coming growing seasons, sunflower growers in Israel will be requested to implement the action threshold in parts of their fields under close supervision by extension personnel. Should the results be satisfactory, implementation of the action threshold will be incorporated in routine recommendations to growers.

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