The Role of Airborne Conidia in Epiphytotics of Sclerospora sorghi on Sweet Corn

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ABSTRACT

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Sclerospora sorghi infected sweet corn (cultivar Jubilee) by soil-borne oospores and through leaves by airborne conidia. Oosporic inoculation resulted only in half-leaf systemic infection whereas conidial inoculation first produced local lesions on the lower leaves and systemic infection developed later. Local infection and the subsequent development of systemic infection was induced by conidia on 3-wk-old or younger plants. Older plants were resistant to conidial inoculum applied to leaves, but became infected systemically when conidia were injected into the stem. Conidial inoculum induced disease if inoculated plants were kept wet for only 2 hr, but 6-8 hr of leaf wetness were optimal. High infection percentages (88%) were obtained in darkness at 20-25 C; increasing conidium concentration resulted in higher incidence of local and systemic infections. The amount of infection from oospores in the field increased from less than 1% in plants from seed sown in March and April to about 5% in plants from those sown in May through August. Conidia were dispersed from systemically infected plants from early June, and systemically infected plants were efficient foci for rapid spread to nearby younger plants. Under commercial field conditions, inoculum from systemically infected plants induced only local infection on plants of the same age. However, younger plants in close proximity to conidia-bearing plants, were heavily infected both locally and systemically. Local infections, as such, did not decrease yield, but 75% of the systemically infected plants produced only one ear or no ears at all. Plots with average systemic infection of 0, 13, and 57%, yielded 16,000, 14,500, and 8,400 kg of ears (fresh wt)/hectare, respectively.

Additional key words: sorghum downy mildew, infection, oospores, epidemiology, crop losses, *Zea mays*.

Sorghum downy mildew (SDM), which is incited by *Sclerospora sorghi* Weston and Uppal, was first recorded in Israel in 1963 on sudangrass, Johnsongrass, and corn (5), and since then severe epiphytotics have occurred in some years on corn (7, 11).

Soil-borne resting spores (oospores) were considered as the primary inoculum for initiating the disease in sorghum and Vidan, especially in late sowings of the crop when soil temperatures were higher. Systemic infection of corn ("half-leaf" symptoms) also was attributed to oosporic inoculum (3). Local infections in corn, which occasionally were seen on the lowest leaves of some sweet corn hybrids, were considered insignificant in disease epidemiology (6). Our observations have indicated, however, that airborne conidia of *S. sorghi* may be important in enhancing epiphytotics of SDM in sweet corn (11).

The present work was undertaken: (i) to determine the significance of airborne conidia in producing disease under lab and field conditions; and (ii) to determine the relationship between disease incidence and yield loss. Some of the results were published earlier (10).

MATERIALS AND METHODS

The sweet corn hybrid, Jubilee, was used in all experiments. For laboratory inoculations, plants were grown in 0.5- or 3-kg pots (3 and 10 plants/pot, respectively) filled with a mixture of garden soil, peat, and vermiculite (2:2:1, v/v) and kept at 25 C with 12 hr of light per day from Sylvania Gro-Lux fluorescent lamps yielding 15,000 lux. In warm months (May-September), plants were grown in the greenhouse. Hoagland's solution was supplied once a week.

Conidia of *S. sorghi* (local race) were collected from infected Vidan *(Sorghum vulgare × Sorghum sudanensis)* plants that were grown and inoculated indoors. Vidan was used because of the abundant sporulation produced on its leaves. The following technique was developed to obtain mature conidia before their in situ germination: systemically infected plants [obtained by exposing very young plants to sporulating *S. sorghi* on infected leaf-segments (3)] were illuminated for 24 hr, placed in darkness at 60-70% relative humidity (RH) for 4-6 hr, and then transferred to a moist atmosphere for 2 hr, all at 20 C. At the end of the moist period, during which profuse sporulation had occurred, conidia were brushed into distilled water and their concentration was determined with the aid of a haemocytometer. Of the various inoculation techniques tested, spraying plants with conidial suspension containing 0.01% Tween-20 was best. Inoculated plants were covered individually with moist transparent polyethylene bags, placed at 20 C for 12-24 hr in the dark (unless otherwise stated), then uncovered and transferred to 25 C (12 hr of light/day at an intensity of 25,000 lux from Sylvania VHO fluorescent light supplemented with incandescent bulbs) at 65-75% RH.

Field observations were done at the Bar-Ilan University campus during 1974-75 and at Azrikam in 1975. On campus, a 200-m^2 plot was sown in late August 1974 in close proximity to a SDM-infected field of Vidan. This field was ploughed down in 1975 and planted to corn again. It was divided into 20 10-m^2 plots. Five of the 10-m^2 plots were sown on each of the following dates: 3 March, 19 March, 4 April, and 15 May. Minimal soil temperature (at a depth of 15 cm) during the emergence periods was 8-9, 9-10, 14-15, and 16-17 C, respectively. Soil samples were taken from each plot when the plots were sown, were transferred into 3-kg pots, and were used for sowing maize in the greenhouse.

A 21-hectare field was sown with Jubilee sweet corn for commercial purposes at Azrikam, in the central coastal plain, 3 km east of the Mediterranean Sea, on 28 June 1975. Corn had been grown on the whole area of this field in 1973, and plants in an adjacent corn field were slightly infected with SDM in 1974. The field was divided into six plots (3.5 ha each, plots A to F) which received the first irrigation (overhead sprinkling, 1,000 m^3/ha) on successive days: plot A on 29 June, plot B the following day, etc. Emergence took place within 6 days after irrigation. Irrigation on successive days produced a gradient of ages of plants in the field. By the time of emergence of plots E and F, plants in plot A had developed two leaves. Disease was assessed on 200 plants in the two central rows of each plot.

A thermohygrograph was placed 1 m above ground in the middle of the field. Temperature and relative humidity (RH) were stable during the first 4 wk after emergence: minimal and maximal temperature was 18-20 and 29-32 C, respectively; minimal and maximal RH was 50-60 and 85-100%, respectively, and duration of RH > 95% per night was 8-12 hr.

To measure the effect of the disease on yield, the number of ears per plant was counted on 500 healthy and 500 systemically infected plants. Ears were collected from plants along 20 m of row in the central two rows of each of the six plots on the 68th day after sowing. Ears from healthy and infected plants were counted and weighed to determine comparative differences in yield. Their protecting leaves were removed and the following developmental characteristics of the ear were determined: ear length, diameter, and weight, and the number of seed rows per ear, seeds per row, and seeds per ear.

RESULTS

Infection under laboratory conditions.—The results presented in Fig. 1-A show that percentage of infected plants increased with increasing inoculum concentration

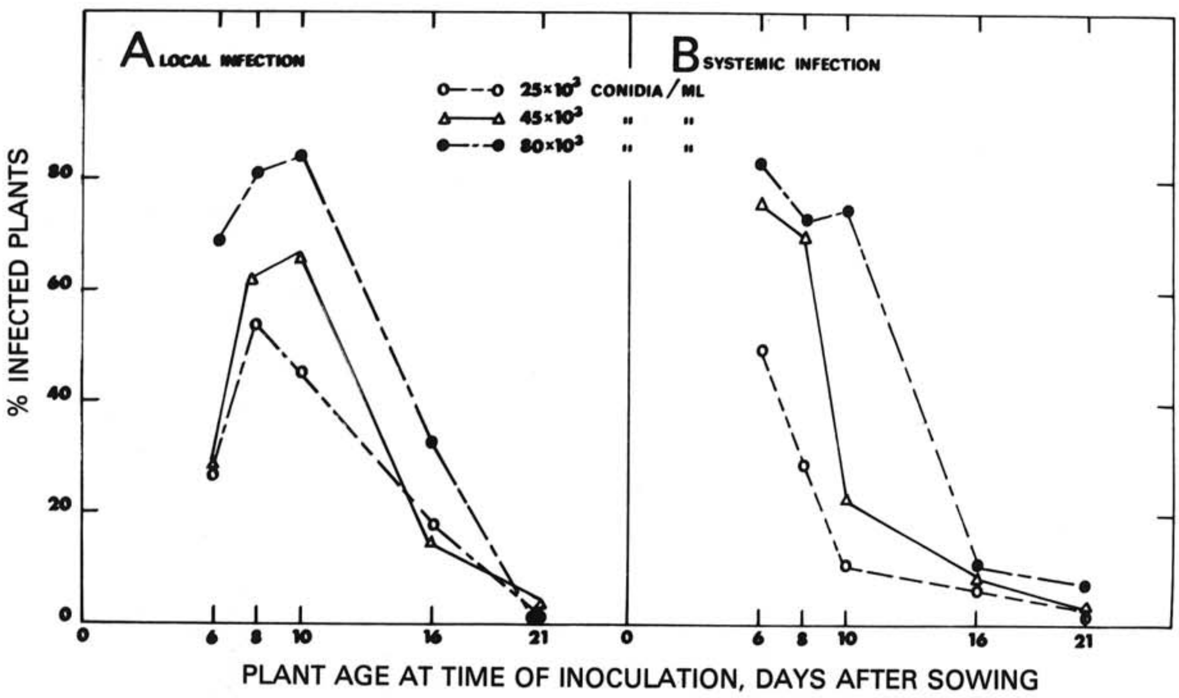

Fig. 1-(A, B). The effect of conidium concentration and age of plants at time of inoculation on percent infection of sweet corn (cultivar Jubilee) by *Sclerospora sorghi.* **A)** Local lesions on the lower two leaves, assessed 11 days after inoculation. **B)** Systemic "half-leaf" symptoms 27 days after inoculation. Plants at indicated age were sprayed with a suspension of 25, 45, or 80 × 10^3 conidia/ml, placed in moist chamber (20 C, in darkness) for 24 hr, and then transferred to 25 C (12 hr light/day) at 65-75% relative humidity.

from 25 or 45 × 10^3 to 80 × 10^3 conidia/ml. Plants inoculated just after emergence (6 days after planting) showed a high incidence of local infection, but those inoculated at the two-, three-, or four-leaf stage (8 and 10 days after planting) developed most lesions. Plants in the five-leaf stage (21 days after planting) were much less susceptible. By the 27th day after inoculation many plants inoculated at the two- and three- or four-leaf stage which had local lesions earlier, had become infected systemically (Fig. 1-B). All plants with local lesions in the coleoptile stage and the five-leaf stage, and even some which lacked local infection on the 11th day, had become infected systemically.

Under laboratory conditions the first local lesions of the disease appeared on the oldest pair of leaves about 1 wk after inoculation. The lesions were elongate and chlorotic, and occurred on the distal ends of the blades. Lesions gradually extended toward the leaf base, and within 1 wk systemic symptoms of the disease were evident in the newer leaves. Half-leaf symptoms developed on the third or fourth leaves from the bottom, but younger leaves were infected completely. Sporulation was induced on both local and systemic infections after a dark moist period of 24 hr at 20 C.

The susceptibility of five- to six-leaf corn plants was tested in two other experiments. In the first, 19- and 23-day-old plants (50/treatment) were inoculated with a suspension of conidia; 18 and 5% of the plants developed local infections, respectively. In the second experiment, similarly inoculated 22- and 24-day-old plants (100/treatment) developed 6.5 and 2.5% systemic infection, respectively.

The effect of leaf wetness duration.—A second series of experiments was conducted to determine the effect of

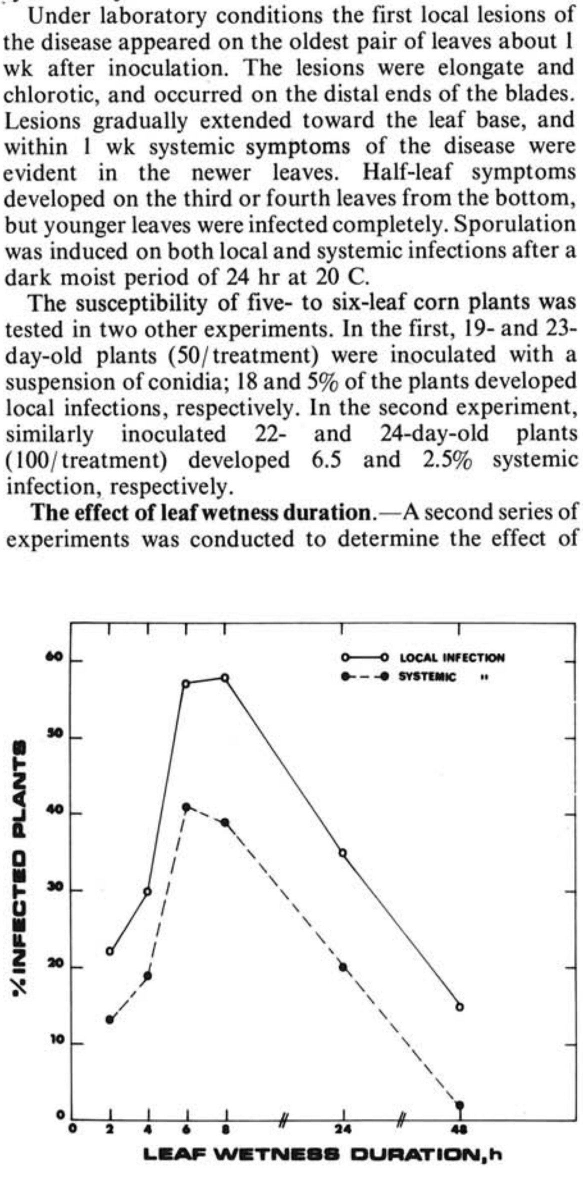

Fig. 2. The effect of leaf-wetness duration after inoculation (20 C, darkness) on percent infection of sweet corn with *Sclerospora sorghi*. Nine-day-old plants (three-leaf stage) were sprayed with a suspension containing 50 × 10^3 conidia/ml. Local and systemic infection was assessed 8 and 15 days after inoculation, respectively.

duration of wetness after inoculation on development of local and systemic infection. The results (Fig. 2) show that local infection (22%) occurred on inoculated plants that had as little as 2 hr of leaf wetness. The highest level (57-58%) was attained in the 6- to 8-hr treatments, but infection was significantly decreased by lengthening of the moist period. This type of decrease in infection induced by prolonged wetting periods is known in other downy mildews such as those caused by *Plasmopara halstedii* (1), *Phytophthora infestans* (8), *Peronospora tabacina*, and *Pseudoperonospora cubensis* (Y. Cohen, *unpublished*). The number of plants with systemic infection was lower, and directly correlated with the reduction in local infections 1 wk earlier. Leaf wetness durations of 2, 6, and 48 hr after inoculation resulted in 13, 41, and 2% of systemic infection, respectively.

Production of local lesions and the subsequent development of systemic infection was examined at 15, 20, and 25 C, either in light (200 $\mu E\ m^{-2}\ s^{-1}$) or in darkness. The results showed that more plants developed local infection if incubated at 20 C or 25 C in the dark (73-78%) than if incubated in the light (55-56%). The opposite was true for 15 C; 55% developed local lesions if incubated in darkness and 66% if incubated in the light. By the 11th day after inoculation, most plants were infected systemically. However, only a few plants with systemic infection had no local lesions on their two lowest leaves.

Three repetitions of this experiment proved that incubation in darkness at 20 or 25 C gave rise to more infections than in the light.

Inoculations in light and darkness also were undertaken at 20 C with three different inoculum doses: 40, 110, and 200 × 10^3 conidia/ml. Percentage of plants showing local infection was 45, 65, and 72% if incubated in darkness and 27, 34, and 56% if incubated in the light, respectively.

The transition from local to systemic phase of the disease was observed on two-leaf, 8-day-old plants. Of 95 plants inoculated at 20 C, 65 developed local lesions on one or both leaves by the 9th day after inoculation. One week later, 33 of the 65 locally infected plants (four- to five-leaf stage) had developed half-leaf systemic infection, nine on the third leaf and upward, and 24 on the fourth leaf and upward. The third leaf of these 24 plants was free of any visible symptoms, indicating that most plants had developed the third leaf before the pathogen moved from the first and second locally infected leaves into the upper leaves, probably through invasion of the "stem". No systemic symptoms developed on those plants which had no local lesions on their lower leaves, suggesting that conidia could induce systemic infection only if local infection had occurred earlier.

A more "natural" inoculation process was achieved by exposing potted corn plants to conidia dispersed from infected Vidan plants (see Materials and Methods). Three hours of exposure to conidia of 7- and 10-day-old plants at 20 C (100% RH) in the dark resulted 4 days later (at 25 C) in 56% and 72% locally infected plants, respectively. On the 7th day after inoculation about 90% of the plants had developed local lesions.

In another experiment, three-leaf plants (36-58/treatment) were exposed for either 1, 2, or 3 hr to conidia dispersal at 20 C in a saturated atmosphere. On the 5th day after inoculation 55, 87, and 90% of the plants

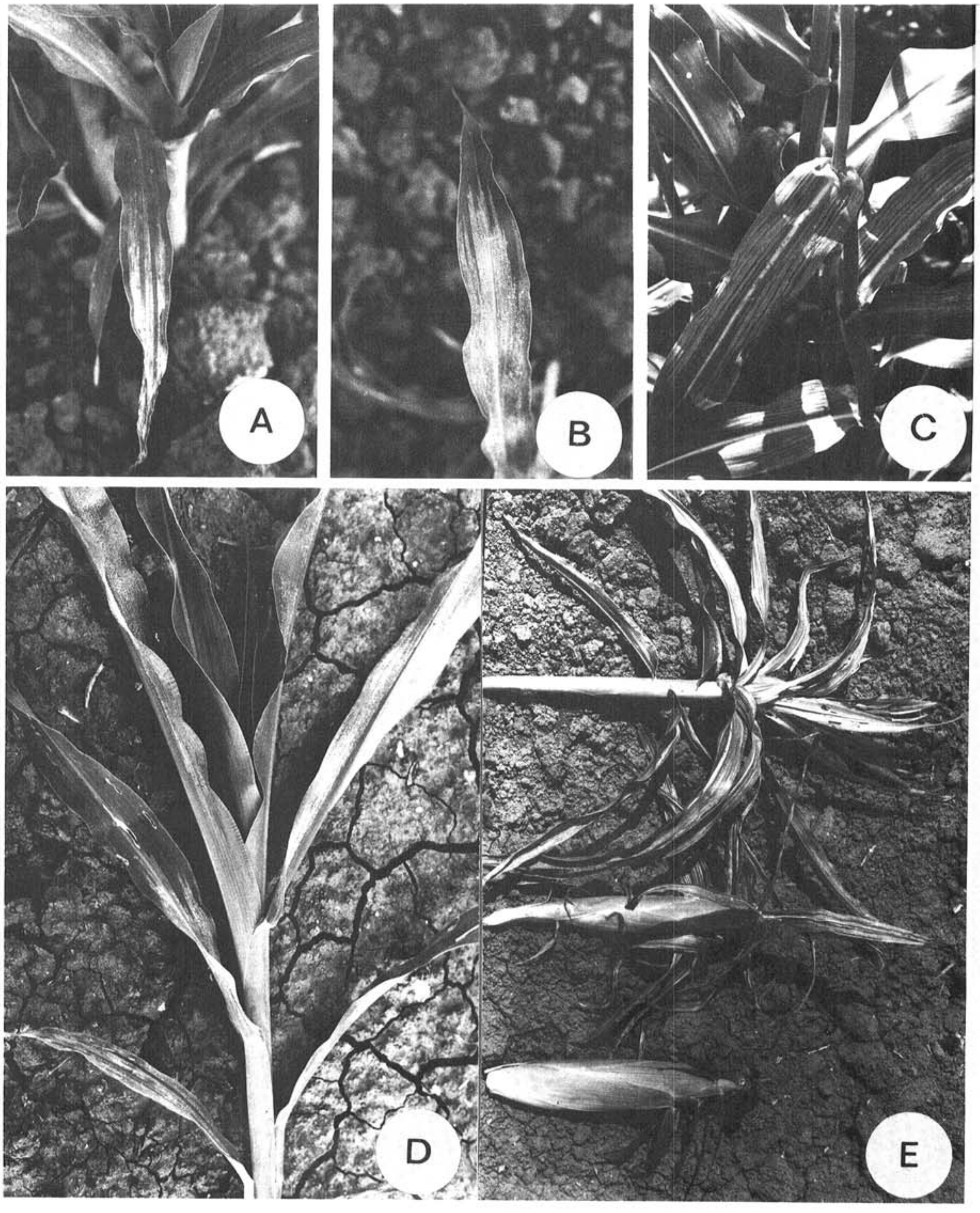

Fig. 3-(A to E). Symptoms of downy mildew on sweet corn (cultivar Jubilee). **A)** Local infection with *Sclerospora sorghi*, 3 wk after emergence. **B)** Systemic infection ("half-leaf" symptoms) 3 wk after emergence. **C)** Striping of sorghum downy mildew on upper leaves of sweet corn directly below the tassel. Infected tissue contained oogonia and oospores. **D)** Local infection and systemic infection on a nine-leaf plant. Note local infection on leaves (from bottom upward) 1, 2, and 3; half-leaf symptom on leaf 4, and full systemic infection on leaves 5-8. Symptoms are not evident on leaf 9. Note heavy sporulation on the middle leaves. **E)** The effect of sorghum downy mildew on ear development. The ear on bottom is from a healthy plant; the other two are from systemically infected plants. Note the abnormally elongate shank leaves of the upper ear, and the striping on both.

had developed local infection, respectively.

When 10-day-old (two- to three-leaf) plants and 27-day-old (six- to seven-leaf) plants were exposed for 1 wk to sporulating Vidan donors (at 20 C, 12 hr of wet and darkness per day), 80 and 12% became locally infected, respectively. However, 3 wk after inoculation 75% of the young plants developed systemic infection, whereas none of the older plants did so. The results presented above indicate that corn is susceptible to SDM for about 3 wk, but older plants are resistant. By injecting conidial suspension of *S. sorghi* into the stem (below the first leaf) of potted or field-grown corn plants of various ages (up to 36 days old), it was revealed that plants of all ages were highly susceptible to the pathogen. This supported the assumption that the failure of conidial inoculum to produce SDM in > 3-wk-old corn is probably due to the development of some anatomical barrier in the host plant.

Infection under field conditions.—Observations made in 1974 (200 m^2 on campus) showed that 20 days after sowing (14 days after emergence) 81% of the plants had local lesions of SDM on the two oldest leaves, but only one plant of several hundreds had systemic, half-leaf symptoms. Within another week, the percentage of locally infected plants had increased to 90%. Systemically infected plants were counted 2, 3, 4, and 7 wk after emergence. Their percentage in the population was 0.8, 25, 41, and 83%, respectively. Abundant oospores were observed microscopically in systemically infected leaves, particularly after striping appeared on upper leaves. In 1975, 1 mo after sowing, a very small proportion of the plants had systemic symptoms of the disease; in the field 0.6, 1.2, and 0.8%, and in the greenhouse 1.2, 1.1, and 1.5% of the plants sown on 3 March, 19 March, and 4 April, respectively. No local infections were evident on plants sown in March and April, indicating that the disease was induced by soil-borne oospores. More detailed records were taken in the plot sown 15 May. Plants emerged, and were exposed to airborne conidia from adjacent diseased Vidan and corn plots, 5-6 days after sowing. Disease was not observed on the 13th day (four-leaf stage) after emergence, but on the 18th day (seven-leaf stage) 96% of the plants had local lesions on their first, second, or third lowest leaves. On the same day, 4.3% and 7.7% of the plants were systemically infected in the field and in the greenhouse, respectively. The amount of systemic infection continued to increase in the field, and reached 11, 30, 58, 80, and 82% by the 22nd, 25th, 30th, 34th, and 49th day after sowing, respectively. Three times more infected plants were present in the northeastern plots than in the western ones, probably owing to the southwestern winds that occur in the area in early morning.

Another 300 plants were sown in an adjacent, *Sclerospora*-"free" soil, on 8 June. Within 2 wk, all plants were locally infected with SDM, and in another 12 days, 90% were infected systemically.

Disease records in the field of Azrikam were taken first on 27 July 1975 (1 mo after sowing). On this date, plants in plot A (irrigated first, 29 June) had 10 leaves, and those in plot F (irrigated last, on 4 July) had six to seven leaves. At this developmental stage, most plants (62-100%) had local infections (Fig. 3-A), but only 0.5-33% were infected systemically (Fig. 3-B). There were characteristic, elongate, chlorotic lesions on the locally infected plants. Most lesions had developed on the distal end of the leaf. On dewy mornings, white down (conidia + conidiophores) was evident on both sides of the infected leaves. Local lesions had developed at this stage on the older leaves only. Plants in plots A-D had local infections on the three lowest leaves (Fig. 3-D), and those in plots E and F, on the five lowest leaves. Plants in plots A-C already had developed four to five tiller leaves and local lesions had developed on the lower two leaves. Symptoms

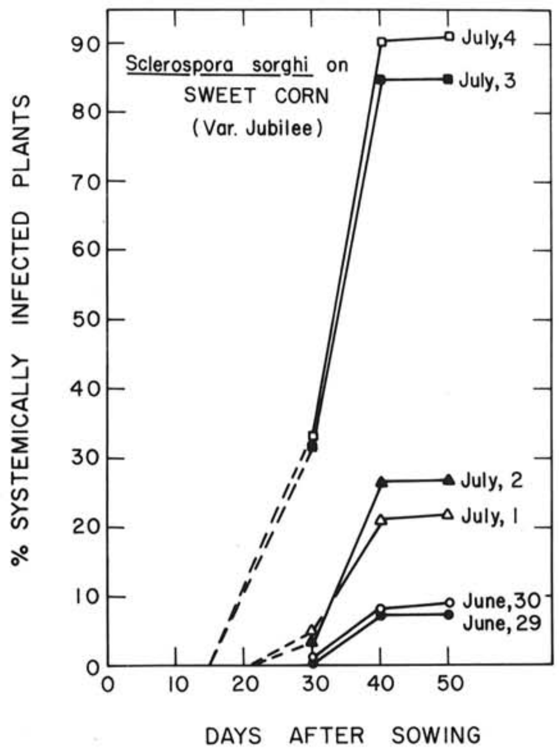

Fig. 4. Epiphytotic of sorghum downy mildew in commercially-grown sweet corn sown on 28 June. Field was divided into six plots. Germination was induced by irrigation on the dates indicated on the curves. By the 50th day, all plants had local lesions. Thus, the y-axis represents only percent of systemic infection.

TABLE 1. The effect of systemic downy mildew infection of sweet corn (cultivar Jubilee) on the corresponding yield losses in a commercially grown field

Plot	Systemic infection (%)	Total yield (kg/20 m^2)	Yield loss[a] (% of healthy)
A	6	43.6	3.2
B	9	46.4	0
C	27	30.6	32
D	22	20.5	54.5
E	85	17.7	60.7
F	91	4.3	90.5

[a]Average yield of healthy plants was 45 kg/20 m^2. The amount of disease and comparative yields of diseased and healthy plants was assessed 68 days after sowing on 58-78 plants from each 20 m^2 plot.

of systemic infection (half-leaf symptoms, Figs. 3-B and 3-D) were present mainly on the third and fourth leaves from the base and upward.

The percentage of systemically infected plants greatly differed among the various plots of the field; plants in the plots which germinated earliest had much less disease (0.5%) as compared to the plants in the other plots (32-33%).

Forty days after sowing (7 August) plants had reached 80-120 cm in height, depending on the date of germination, and had two to five tillers. The five lower leaves on the main stem and also on the tillers all (1,200 plants in six plots) had local lesions. Also, some plants had restricted sporulating local lesions (1-3 cm long, 0.5 cm wide) on leaves 8-10. All plants were locally infected and within the 10 days that elapsed between the 30th and 40th day after sowing, systemic infection had developed in 85-92% of the plants in the two younger plots, whereas there was only 7-8% systemic infection in the older plots. Plants of intermediate age had an intermediate amount of systemic infection (22-27%). No further significant increase in amount of systemic infection was recorded from this date until harvest (Fig. 4).

In mid-August, tassels and ears already had developed on plants in the oldest plots, whereas tassels only were present on the youngest plants. The ear-protecting leaves (and sometimes the shanks) of systemically infected plants were abnormally elongated, and had sporulating, striped, and chlorotic lesions (Fig. 3-E). The uppermost leaves of the main stem directly below the tassel also had striped lesions (Fig. 3-C). Microscopical examinations revealed that oogonia and oospores were abundant in the stripes, and especially so in necrotic tissues.

Crop losses.—Ninety-five percent of the healthy plants developed two ears per plant, and only 5% had one ear per plant. Of the diseased plants, 50%, 24%, and 26% had 2, 1, and 0 ears per plant, respectively. Yield of ears on locally infected plants which escaped systemic infection was not reduced.

Length, diameter, and weight of the ears were reduced by 35, 25, and 60%, respectively, and about 30% fewer seeds were produced on the ears from infected plants.

Results presented in Table 1 show a close correlation between the percent of systemic infection and yield loss. Yield was greatly decreased in severely attacked plots. Thus, plot F yielded 10 times less ears by weight (4.5 times less by number) than did plot A.

Commercial harvest (for canning) of the western A, B, and C plots was done on 4 September and from plots D, E, and F on 7 September. Fresh weights were 14,500 and 8,400 kg/ha in the western and the eastern halves of the field, respectively.

DISCUSSION

Although Frederiksen et al. (3), Kenneth and Klein (6), and others [see literature cited by Frederiksen et al. (3)] indicated that airborne conidia of *S. sorghi* may be important inoculum for sorghum and hybrids, no clear-cut evidence has been reported on the role of conidia in epiphytotics of the disease on corn under field conditions.

Although laboratory studies showed that conidia induced infection of young corn seedlings that later developed systemic symptoms (9, and the literature cited therein), the significance of these results in the field was not determined.

Our results clearly indicate that conidia of *S. sorghi* may infect aboveground parts of corn plants until about 3 wk after emergence. Although the leaves of 5-wk-old plants remained susceptible to local infection, systemic infection did not develop unless conidia were injected into the inner tissues of the stem.

Local infection on the lower leaves could be clearly distinguished from systemic infection, because local lesions were elongate, chlorotic, and usually developed on the distal leaf ends. A gradual expansion of the lesions toward the base of the blade was evident within a few days, and systemic (mostly "half-leaf") infection followed rather soon. We assume that systemic spread of the pathogen in the plant shoot occurs only if the fungus reaches the apical meristem in the base of the young "stem". A similar transition from local to systemic infection also occurs with sunflower downy mildew which is incited by *Plasmopara halstedii* (1).

Depending upon plant age and environmental conditions, a high proportion of locally infected plants later became infected systemically. This occurred in the laboratory without any further exposure to conidia. Systemic infection was first evident as "half-leaf" symptoms, but upper leaves were completely chlorotic, albeit weakly, and became striped at about flowering time.

The contribution of airborne conidia to epidemic increase under field conditions might be very significant as was observed in our field trials in the Jubilee corn hybrid. However, as was pointed out by Frederiksen et al (3), some cultivars may be more vulnerable to infection from conidia than others.

Similar patterns of disease increase due to conidia of *S. maydis* on corn were observed by Tantera (12) in Indonesia under field conditions.

Development of local infection (produced on the lower two leaves of corn) into systemic infection under laboratory conditions, was reported by Kajiwara (4) in Indonesia (probably working with *S. maydis*) and by Dalmacio and Exconde (2) with *S. philippinensis*.

In large-scale commercial corn production in Israel, it is technically impossible to irrigate the whole field at once. Therefore, fields are divided into plots which are irrigated on successive days. This results in plants of various ages growing in adjacent plots. Thus, we found that a plot which was irrigated first had only 6% systemic infection, whereas another adjacent plot irrigated 6 days later had about 90% systemic infection, although all plants of both plots exhibited earlier local infection.

The soil of our test field in Azrikam probably was infested uniformly with oospores of *S. sorghi*. Also, weather conditions were stable during July (see Materials and Methods). Therefore, we assume that the large differences in disease incidence between the plots in the field were due to difference in airborne conidial inoculum. It seems likely that initial conidial inoculum was produced on a few systemically infected plants in the plots that were irrigated first. By the time that conidia began to disperse from these foci (about 10 days after emergence) plants of the other plots, irrigated later, had developed one to three leaves. As proneness of corn seedlings to develop systemic infection from local lesions decreases sharply with age [see the Results section and (2, 4)], it seems likely that the sequential gradient in plant development over the field coincided with a parallel gradient in proneness, and thus in widely different final percentages of systemic infection.

The calm winds (5-6 km/hr) blowing from the southwest during early morning (0500 to 0700 hours) could probably carry conidia (dispersing between 0200 to 0400 hours) (10), to the younger plants in the eastern plots. Therefore, we have recommended that irrigation in such fields should start from the east and progress to the west, so that foci of infection first produced in the eastern plots will not threaten younger plants in the western plots. Preliminary results collected in 1976 indicated that this procedure resulted in a decrease in the incidence of disease.

Crop losses were closely correlated with the proportion of systemic infection in the population. As was observed by many workers [(3) and literature cited therein], systemically infected plants produce no grains. In our study, ears of infected plants, if produced, were unsuitable for marketing, and therefore were a total loss.

Our laboratory studies support the assumption that conidial showers, arriving at an advanced stage in plant development ($\geqslant$ five- to six-leaf stage), induce only local lesions. Thus, systemic infection would not take place and yield should not be reduced.

The results presented here suggest that a precise timing of an appropriate fungicide application could control local infection and thus greatly reduce systemic infections and crop losses.

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