Influence of Soil Solarization at Moderate Temperatures on Potato Genotypes with Differing Resistance to *Verticillium dahliae*

J. R. Davis and L. H. Sorensen

Professor and research associate, respectively, Department of Plant, Soil and Entomological Sciences, University of Idaho Research & Extension Center, Aberdeen, ID 83210.

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ABSTRACT

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A 3-yr study involving solar heating of the soil (solarization) with polyethylene mulching demonstrated disease suppression and significant improvements in yield and quality of potato. This occurred at maximum air temperatures with a mean of 26–33 C on a weekly basis and with elevations of soil temperatures that were believed to be marginal for inoculum reduction (mean of 26 C compared with 41 C at 15 cm for nonmulched and mulched sites, respectively). Common scab (*Streptomyces scabies*) was suppressed, belowground stem lesions were reduced (associated with *Rhizoctonia solani* AG-3 and *Colletotrichum atramentarium*) and Verticillium wilt (*Verticillium dahliae*) was effectively controlled. Total yields of cultivar Russet Burbank were increased by 46%, and the amount of U.S. #1 tubers was improved by 118%. A potato clone (A68113-4) with a high degree of resistance to *V. dahliae* also responded positively to the solarization treatment (18% increase of total yield and 25% increase of U.S. #1 potatoes). Lasting effects of suppression of *V. dahliae* were evident for 2 yr after treatment.

Additional key words: crop production, increased growth response, potato early dying.

Soilborne plant pathogens cause severe losses to potato (*Solanum tuberosum* L.). Among these pathogens, *Verticillium dahliae* Kleb. (causal organism of Verticillium wilt) remains as one of the most significant limiting factors for the production of this crop. Yield losses of 56–112 q/ha are not uncommon and losses that exceed 30% have been documented in Idaho (5,6). Verticillium wilt of potato may be controlled directly by soil fumigants (e.g., chloropicrin or methyl bromide and metam-sodium), but use of these fumigants is widely limited by cost. The search for new, simple, inexpensive, and nonhazardous methods for control continues.

During recent years solar heating of the soil (solarization) was developed in Israel (18). In the warm regions of the Negev desert in Israel and the San Joaquin Valley of California, the dramatic effects of soilborne disease suppression are well documented (14,16,17,19–21,24–27). Evidence even exists for success with soil solarization in the cooler areas of England (30).

In contrast to the desert regions of Israel and California, the climate in the potato-growing areas of Idaho is generally cooler. Although it is recognized that the use of soil solarization for potato production may be limited by cost, this approach offers several potential values.

In addition to the physical effects of heat, the microbial processes that are induced by solarization also may contribute to disease control. One of the potential benefits to be anticipated with solarization is the lasting effect that has been associated with biological control (14,17,19,28). These possibilities may be particularly useful in regions where the cumulative effect of heat may be insufficient for disease control (e.g., in cool areas with moderate temperatures and at deeper soil layers). Benefits from solar heating also may exist with increased growth response (3,17,28), providing the possibility for yield benefits with resistant genotypes. To investigate the possibility of increased growth responses, potato selection A68113-4 was chosen for our solarization studies. This clone possesses a high degree of resistance to *V. dahliae* (9–11).

The investigation described in this paper documents the effects of solarization under the moderate temperature conditions of southeastern Idaho. The effects of solarization were assessed on three potato clones possessing differing levels of resistance to *V. dahliae*, the effects on common scab were documented, and the lasting effects of solarization were investigated for three consecutive years. Abstracts describing a portion of this work have been published (12,13).

MATERIALS AND METHODS

Solarization treatment and soil assays, 1980. The site selected for solarization studies was on a coarse textured, loam soil at the University of Idaho Research & Extension Center, Aberdeen. During the year preceding solarization, this field had been cropped with potatoes and before that, the field had a history of potato and grain rotations of more than 30 yr. In the spring of 1980, when solarization treatments were initiated, a green manure crop of barley was planted and disked under several days before polyethylene was positioned. At the time of disking the barley was less than 15 cm high.

The experiment was designed as a randomized complete block with six replications of 12 treatments. Thirty-six of the plot sites were treated both with and without solarization. Each plot site was 7.3 × 12.8 m.

In preparation for solar heating, trenches about 15 cm deep were cut around each plot. To assure adequate moisture, the field was preirrigated with a sprinkler irrigation system before the polyethylene sheets were positioned.

On the morning of 18 June, 4-mil (0.10 mm) sheets of clear polyethylene were secured in position in the surrounding trenches and covered with soil along the plot edges. At that time, the soil moisture was at field capacity within the uppermost 0.6 m of the soil profile. Two hours were required to position the polyethylene; during this time the drying of soil was insignificant.

Temperatures were monitored with eight Tempscribe

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continuous recording thermometers (Bacharach Instrument Co., Pittsburgh, PA). At two widespread localities within the field, temperatures were continuously recorded at 15- and 30-cm depths, and the variability of temperatures from positions in the field was considered to be insignificant. To estimate the variability of temperatures among plot sites, 20 additional soil thermometers were randomly positioned in plot locations at a 10-cm depth. The range of temperature variability in the tarped and untarped areas was less than 2.2 C.

On 4 August, thermometers and polyethylene sheets were removed from all plot sites. The accuracy of temperature recorders was determined by recalibrating them at the conclusion of the solarization treatments and the accuracy of recorded temperature values was reverified.

During the season, weeds in the nonsolarized areas were controlled by shallow disking (on 8 and 28 July) at a depth of 5.0–7.5 cm.

Soil samples were collected from two regions in the soil profile (0–15 cm and 15–30 cm) of both the solarized and nonsolarized areas on 9 September 1980 (30 subsamples per replicate were collected for each treatment). Samples from each plot were randomized, air-dried, and assayed for *V. dahliae* as previously described (2). Nematode analyses were determined by G. S. Santo (Northwest Nema-Lab, Prosser, WA) from soil samples that were collected in accordance with recommended procedures. After the polyethylene was removed, the field was allowed to remain fallow until the planting of potatoes in 1981.

Field studies on solarized soil, 1981. Before planting, soil was analyzed for N, P, and K by members of the Department of Plant, Soil and Entomological Sciences, University of Idaho, Moscow, ID. Broadcast applications of fertilizer and sprinkler irrigations throughout the growing season were made in accordance with University of Idaho recommendations. Preplant applications of N and P_2O_5 were made at 179 and 90 kg/ha, respectively. Additional sprinkler applications of N were applied on 14 July and 10 August as a urea-NH_4NO_3 solution with 32% N (Uran) at 45 and 23 kg/ha, respectively, in accordance with dates of application. For weed control, EPTC (Eptam) was applied (preplant) at 3.4 kg/ha a.i. and incorporated within the upper 10–13 cm of the soil.

Treatments consisted of variables involving solarized and nonsolarized plot areas, three potato clones of differing resistance to *V. dahliae* (Russet Burbank, NDA8694-3, and A68113-4), and potato seed that had been disinfested with 0.5% NaOCl or not disinfested.

Potato seed was obtained from the University of Idaho Tetonia Experiment Station, Tetonia. This seed met Idaho certification standards (it was also free of potato virus X and Y). From each clone, 30 tubers were collected per sample and thin slices (~1 mm thick) were removed from the stem ends of each tuber and assayed for fungal infection as previously described (10). Seed sources were free of intratuber infection of both *V. dahliae* and *Colletotrichum atramentarium* (Berk. & Br.) Taub (syn. *C. coccodes* (Wallr.) Hughes). All seed was hand cut at 57 ± 14 g and uniformly planted with an assist-feed potato planter on 7 May (spacings between rows and seed pieces were 0.9 and 0.3 m, respectively). At planting, disulfoton (3.4 kg/ha a.i.) was sidedressed for insect control with a continuous belt applicator.

Four days before foliar N applications on 14 July, a commercial testing laboratory (Stukenholtz Laboratory, Twin Falls, ID) monitored N levels in solarized and nonsolarized plots from composite-sample collections of petioles. Immediately before foliar N applications, the NO_3-N levels were adequate for plant growth (>16,000 ppm N). Sixty petioles per plot were also collected for quantitative determinations of P, S, K, Zn, Fe, and B (University of Idaho, Moscow, ID).

On 10 July, 3 m of plot row were hand dug in each Russet Burbank plot and belowground stems were evaluated for early tuber yield and for symptoms of the Rhizoctonia canker of potato as previously described (5). From lesions, routine isolations were made onto sodium polypectate medium (2) and the selective medium for *C. atramentarium* described by Farley (15).

On 30 July, 20 stems were collected from each plot that had been planted with disinfested seed. Stem sections were cut 1.3 cm above the soil line. The stems were evaluated for symptoms of vascular discoloration and the percentage with discolorations was determined.

Samples from the upper 7.5 cm of the stem (30 per plot) were similarly collected on 29 July and 13 August to measure the colony-forming units (cfu) of *V. dahliae* per gram of stem tissue (11). A portion of the potato stem tissue collected on 29 July also was used to determine the total N content in plant tissue by standard Micro–Kjeldahl procedures.

On 4, 12, and 19 August the percentages of stems with Verticillium wilt symptoms were determined, using a standard procedure (11).

From plot rows that had not been used for either early harvest or stem discoloration data, 21.4 m of row were harvested in each plot on 1 and 2 October. Yields were determined and U.S. #1 grade was evaluated (1).

The incidence of common scab on A68113-4 (a clone with a high

TABLE 1. Influence of solarization on populations of nematodes and *Verticillium dahliae* 1 mo after tarp removal in field plots solarized or nonsolarized in Aberdeen, ID, in 1980

Soil treatment	Soil depth (cm)	Nematodes/250 cm^3 soil[x] Pratylenchus	Tylenchorhynchus	Helicotylenchus	*V. dahliae* (cfu/g of soil)
Nonsolarized	0–15	26.3 a[y,z]	9.0 a	2.3 a	9.7 a[y,z]
Solarized	0–15	9.0 b	4.7 a	0.2 a	0.3 b
Nonsolarized	15–30	28.3 a	10.2 a	2.2 a	10.0 a
Solarized	15–30	32.3 a	4.7 a	0.2 a	8.0 a

[x] Soil collected 9 Sept. 1980 (>1 mo after tarp removal).

[y] Different letters in the same column denote significant differences (P = 0.05) according to Duncan's multiple range test.

[z] *V. dahliae* and nematode populations in nonsolarized ground did not decrease between solarization (15 June 1980) and soil collection (9 Sept. 1980).

TABLE 2. Soil temperatures at Aberdeen, ID, in solarized and nonsolarized field plots

Soil treatment	Soil temperatures (C) at depths[a] 15 cm Mean max Mean	15 cm Mean max Range	30 cm Mean max Mean	30 cm Mean max Range
Nonsolarized	26.0	24.0–28.0	23.3	21.5–25.0
Solarized	40.9	37.0–44.0	33.3	31.0–36.5

[a] Temperatures recorded weekly from 24 June 80 to 3 Aug. 80. Mean maximum air temperature was 29 C. The range of mean maximum air temperature per week was 26–33 C.

TABLE 3. Influence of soil solarization on belowground stem lesions[v] and early yield data of potato cultivar Russet Burbank in solarized or nonsolarized field plots at Aberdeen, ID, in 1981

Treatment	Index of lesion coverage[w] 10 July	Stems free or nearly free of lesions 10 July (%)	Tuber weight 10 July (g/3 m of row)
Nonsolarized (NS)	9.61 ab[x]	50 ab	1179[y]
Solarized (S)	8.23 b	60 b	1351
NS, seed disinfested[z]	11.73 a	38 a	1265
S, seed disinfested	7.12 b	61 b	1262

[v] Symptoms resembled Rhizoctonia lesions caused by *Rhizoctonia solani* AG-3 but were darker in color than typical Rhizoctonia lesions. Isolations from lesions indicated a consistent recovery of two pathogens: *R. solani* AG-3 and *Colletotrichum atramentarium* (syn *C. coccodes*).

[w] Higher index values indicate a greater incidence of disease severity.

[x] Different letters in the same column denote a significant difference (P = 0.05) according to Duncan's multiple range test.

[y] Differences not significant.

[z] Seed washed and disinfested with 0.5% NaOCl before planting.

degree of resistance to *V. dahliae* and susceptibility to *Streptomyces scabies* (Thaxter) Waksman & Henrici) was evaluated as previously described (7).

Field studies on solarized soil, 1982. In 1982 Russet Burbank was planted over the same plots of 1981. Cultural management practices and assay procedures of 1982 were similar to those of 1981. Before planting, a broadcast application of N and P_2O_5 was applied at 252 and 154 kg/ha, respectively, in accordance with soil test results. EPTC for weed control was applied as in 1981. On 3 May, before planting, soil samples were collected from each plot within the upper 23 cm of the soil and assayed for *V. dahliae* (2).

Single drop (whole) Russet Burbank seed was obtained from the same source as 1981 and was also assayed for fungal infection as in 1981. This seed, too, was free of intratuber colonization by both *V. dahliae* and *C. atramentarium*. To reduce the possibility of surface contamination, all seed was washed and disinfested with freshly prepared 0.5% NaOCl. For insect control, disulfoton was applied as in 1981. Potatoes were planted on 5 May 1982.

For NO_3-N analyses, 60 petioles were uniformly collected per plot on 7 July and analyzed by standard procedures. On 27 July an additional broadcast application of 45 kg/ha of N was applied through sprinkler lines.

On both 31 July and 12 August aerial applications of mancozeb were applied at recommended rates for early blight control.

Apices of potato stems (30 per plot) were collected on 26 August to determine the relative degree of colonization of *V. dahliae*, and the incidence of Verticillium wilt was determined on 1 September.

From each plot, 18 m of row were harvested on 29 September, and yield and grade determinations were made by standard procedures.

Throughout all investigation, analyses of variance were made in accordance with appropriate statistical designs and differences were tested for significance by Duncan's multiple range test with a protected *F*-value.

RESULTS

The population of *V. dahliae* was reduced with solarization treatment by 97% within the uppermost 15 cm of the soil (Table 1), and populations of *Pratylenchus* sp. also were reduced in that region. In contrast, reductions of population were not evident within the 15–30 cm zone for either *V. dahliae* or *Pratylenchus* sp. The elevations of soil temperatures with the solarization treatment were regarded to be marginal for reduction of *V. dahliae* (mean maximum of 26 C compared with 41 C for both solarized and nonsolarized sites at the 15-cm depth) (Table 2). The mean ambient air temperatures of 1980 were considered to be normal for Aberdeen. While tarps were applied to the soil in 1980 (18 June to 4 August), the mean maximum air temperatures were only 0.6 C higher than the mean maximum air temperatures of 1980 and the preceding 3 yr. The ranges of maximum air temperatures for 1977, 1978, 1979, and 1980 were also similar during the time of solarization. The range of temperature maximum was 19–35 C for all four years, while the range for 1980 was 20.5–35 C. Similarly, the mean precipitation during the same period was also nearly the same as in 1980 (1 cm average for the 4-yr period compared with 7 cm in 1980).

Although the effect on pathogen suppression appeared to be limited to the upper 15 cm, benefits for disease control and increased yield occurred the following year (1981). Early in the growing season (10 July), evidence was provided for a suppression of belowground stem lesions that resembled the Rhizoctonia canker of potato (Table 3). Isolations from these lesions showed the recovery of both *Rhizoctonia solani* Kühn AG-3 and *C. atramentarium*. Either or both of these pathogens could have caused belowground canker development (6). Although differences of lesion development on belowground stems were evident early in the season, yield differences at that time were not significant. Nitrogen levels were sufficiently maintained throughout the growing season for maximum yield, and nutrient availabilities of P, K, S, Zn, Fe, and B did not differ significantly among treatments.

Yet, as the growing season developed, yield differences did occur. These yield benefits were closely correlated (significant at $P = 0.001$) with the log (n+1) values of colony-forming units for *V. dahliae* in potato stem tissue ($r = -0.735$ and $r = -0.685$ for total and U.S. #1 yields, respectively). Likewise, the log values of colony-forming units of *V. dahliae* in potato stems (colonization) were found to be highly correlated ($P = 0.0001$) with the incidence of wilt ($r = 0.816$ and 0.765 for percent wilt observed on 12 and 19 August, respectively).

The incidence of Verticillium wilt symptoms varied for three different potato clones on solarized and nonsolarized soils (Table 4). Among the clones compared, NDA8694-3 was most

TABLE 4. Influence of soil solarization on severity of wilt caused by *Verticillium dahliae* among three potato clones in field plots at Aberdeen, ID, in 1981

Potato clone treatment[s]	Wilt symptoms[t] (%) 4 August	Wilt symptoms[t] (%) 12 August	Severe wilt[u] 19 August	Vascular discoloration[v] of stems (%) 30 July	*V. dahliae* ($\log_{10}$ [n+1] cfu) per gram of stem tissue[w] 29 July	*V. dahliae* ($\log_{10}$ [n+1] cfu) per gram of stem tissue[w] 13 August
NDA8694-3						
Nonsolarized (NS)	58 a[x]	77 a[x]	40 a[x]	...[y]	...	...
Solarized (S)	16 b	31 b	10 bc	...	...	...
NS, seed disinfested[s]	57 a	74 a	32 a	43.3 a[x]	2.46	3.99 a[x]
S, seed disinfested	18 b	35 b	14 b	13.3 b	1.58[z]	3.66 a
Russet Burbank						
NS	15 b	34 b	7 c	...	...	...
S	1 c	5 c	3 d	...	...	...
NS, seed disinfested	18 b	29 b	8 c	30.1 a	...	2.58 b
S, seed disinfested	0 c	1 cd	1 de	5.8 bc	...	1.40 c
A68113-4						
NS	2 c	0 d	0 e	...	...	...
S	0 c	2 cd	0 e	...	...	...
NS, seed disinfested	0 c	3 cd	0 e	11.1 bc	...	1.52 c
S, seed disinfested	2 c	2 cd	0 e	4.2 c	...	0.00 d

[s] Seed disinfested with 0.5% NaOCl before planting.

[t] Yellow, wilted foliage on upper 15 cm of stem.

[u] More than 75% of stem affected.

[v] Stems (20 per plot throughout same given rows of respective replicates, cut about 1.3 cm above soil line) with two or more discolored vascular bundles.

[w] Randomly collected from upper 7.5 cm of stem.

[x] Different letters in same column denote significant differences ($P = 0.05$) according to Duncan's multiple range test.

[y] Data not collected.

[z] Significant difference in column at $P = 0.10$.

susceptible, Russet Burbank was less susceptible, and A68113-4 was most resistant. For the two susceptible clones, solarization consistently suppressed the disease. On three dates of observation these relationships remained consistent. Observations of vascular discoloration and the relative degrees of colonization by *V. dahliae* within potato stem tissue confirmed their relationships to Verticillium wilt. Because the treatment effects between disinfested and nondisinfested seed were not significant, there was no evidence for the introduction of inoculum of *V. dahliae* with the seed. Solarization reduced colonization of *V. dahliae* of the resistant clone A68113-4, which again indicates reduction in soil population of *V. dahliae* (Table 4).

Yield and grade responses were associated closely with Verticillium wilt (Table 5). Consistently, even with the highly resistant A68113-4, yields of both total and U.S #1 potatoes were significantly improved by solarization. The mean total yield increases for the NDA8694-3 clone ranged from 31 to 37%, and for U.S. #1 tubers yield increases ranged from 46 to 57%. Similarly, total yield increases for cultivar Russet Burbank ranged from 31 to 46%, whereas U.S.#1 tubers were increased by 65–118%. Although yield increases were less dramatic with the highly resistant A68113-4 clone, significant benefits also were evident (15–18% increase of total yield and 18–25% increase of U.S. #1 potatoes). Although the solarization treatment had no effect on the percentage of malformed tubers, with solarization, tubers were bigger. Also, with NDA8694-3, the solarization treatment significantly increased the specific gravity of tubers.

Although common scab of potato (caused by *S. scabies*) was not an economic problem in this experiment, the highly scab-susceptible A68113-4 clone did show evidence of scab. Incidence of common scab was suppressed with solarization. The percent by weight of tubers free of scab was 26, 50, 38, and 46% for tubers in nonsolarized, solarized, nonsolarized and seed-disinfested, and solarized and seed-disinfested plots, respectively. Differences between the treatments involving nonsolarization and solarization were significant ($P = 0.05$).

The effect of solarization continued into the second crop year after treatment. The effect of cropping with any of three potato genotypes of differing wilt susceptibility in 1981 had no significant influence on the wilt incidence of 1982. Regardless of cropping history, the incidence of wilt among solarized treatments for cultivar Russet Burbank was consistently lower than that in nonsolarized soil (Table 6). Associated with wilt reduction, the inoculum level of *V. dahliae* in soil and stem colonization were also less. Moreover, wilt severity was correlated ($r = 0.592$, $P = 0.001$ for 36 comparisons) with colonization of *V. dahliae* in stem tissue (Table 6). Slight, but significant, yield increases were evident with solarization and the percentage of cull potatoes was reduced (malformed and undersized). The effects of previous cropping history after 1980 and interactions between cropping history and solarization did not significantly influence yield or wilt incidence.

In contrast to wilt and yield data, assays of *V. dahliae* shown in Table 7 provide evidence for the occurrence of significant interactions, among treatments involving cropping history and solarization. The results demonstrate a significant increase of propagules of *V. dahliae* in Russet Burbank stem tissue in nonsolarized soil after cropping with NDA8694-3 and a decrease in Russet Burbank stems in solarized soil after cropping with A68113-4. Although a similar trend is suggested for populations of *V. dahliae* in soil, these differences were not significant.

TABLE 5. Influence of soil solarization on yield and grade among three potato clones in field plots at Aberdeen, ID, in 1981

Potato clone treatment	Quintals/ha				Percent of grades by weight[w]			
	Total	Increase %	U.S. #1	Increase %	U.S. #1	Malformed[x]	Undersized[y]	Specific gravity
NDA8694-3								
Nonsolarized (NS)	214 f[z]		129 d		51 def	3 c	46 abc	1.075 d
Solarized (S)	293 d	37	202 c	57	59 abc	3 c	38 c	1.079 c
NS seed disinfested	242 ef		139 d		47 ef	5 bc	48 ab	1.076 cd
S seed disinfested	318 cd	31	203 c	46	54 de	4 c	42 bc	1.077 cd
Russet Burbank								
NS	302 d		158 cd		44 fg	6 abc	50 ab	1.083 b
S	395 ab	31	260 b	65	56 cde	7 abc	37 cd	1.085 b
NS seed disinfested	278 de		126 d		37 g	12 a	52 a	1.083 b
S seed disinfested	406 ab	46	274 b	118	58 bcd	5 abc	37 cd	1.085 b
A68113-4								
NS	369 b		283 ab		65 ab	9 ab	26 e	1,091 a
S	424 a	15	334 a	18	67 a	7 abc	26 e	1.091 a
NS seed disinfested	364 bc		272 b		64 abc	7 abc	29 de	1.092 a
S seed disinfested	428 a	18	339 a	25	67 a	7 abc	26 e	1.093 a

[w] Analyses of variance based on arc sine $\sqrt{\%}$ tranformations. Values shown are not transformed.

[x] Malformed tubers >113 g.

[y] Tubers <113 g.

[z] Different letters in the same column denote significant differences ($P = 0.05$) according to Duncan's multiple range test.

TABLE 6. Lasting effects of the 1980 solarization treatment on Russet Burbank at Aberdeen in 1982[v]

Treatment	*Verticillium dahliae* cfu/g[v] of soil 7 May	$\log_{10}(n+1)$ *V. dahliae*/g of apical stems 26 Aug	Severe wilt (%)[w] 1 Sept	Q/ha[w]		Percent of grades by weight[w]	
				Total	U.S. #1	Malformed	Undersized
Nonsolarized	14.0 a[x]	3.00 a[y,z]	38 a[y,z]	335 a[x]	159 a[y]	21.7 a[x]	31.2 a[x]
Solarized	6.0 b	2.62 b	22 b	349 b	184 b	18.7 b	29.0 b

[v] Data summarizes main treatment effects of solarization. In Table 7 interaction relationships are shown.

[w] Interaction relationships resulting from cropping histories with different potato clones or where potato seed disinfestation treatments were not significant.

[x] Different letters in the same column denote significant differences ($P = 0.05$).

[y] Different letters in the same column denote significant differences ($P = 0.01$).

[z] The severity of wilt highly correlated with the degree of colonization of *V. dahliae* in apical stem tissue ($r = 0.592$, $P = 0.001$ with 36 comparisons).

DISCUSSION

At present only three basic approaches exist for the disinfestation of soil (17,18): heating (steam), fumigation, and solarization. Among these approaches, only soil fumigation is widely used and the treatment is practiced with only a small range of materials. Other options for the disinfestation of soil are needed. Although the science of soil solarization is relatively new and this practice has not yet achieved widespread acceptance, possibilities (17) for improved application procedures exist.

Long-term effects of solarization have been documented for a variety of diseases including both Fusarium and Verticillium wilts of cotton (19,27). Similarly, our results demonstrate improvements in potato yield and quality for two consecutive years after treatment by solarization. This study provides the first example of a significant increase of specific gravity of potato tubers with solarization. Yield increases as high as 46% occurred 1 yr after treatment; yields of U.S. #1 potatoes were increased as much as 118%. Combining solarization with the use of a cultivar that is moderately resistant (Russet Burbank) resulted in greater control of the disease than with the more susceptible clone (NDA8694-3) (exemplifying an approach to integrated pest management). Interestingly, all of these benefits occurred even though inoculum density (ID) of *V. dahliae* in soil were low and soil temperature elevations for solarization were marginal (mean maximum of 41 C at the 15-cm soil region). It is anticipated that similar results might occur during most years, since temperature and the degree of precipitation were nearly the same as in the preceding 3 yr. At the time of solarization, meteorological conditions were regarded as normal for the Aberdeen area.

A significant influence on ID of *V. dahliae* occurred only in the top 15 cm of soil. Because potatoes were planted in the region 15 cm below the soil surface and the roots grew throughout the 30-cm zone, the levels of disease control and increased yields achieved were not anticipated.

The relatively greater reduction of disease incidence compared with ID may have been due to either or both of two possibilities: the initiation of soil suppressiveness, thus affecting the capacity of the propagules to produce disease (14,17), and/or an adverse effect on inoculum potential of propagules by sublethal heating, thereby lowering their capacity to produce disease (22).

This investigation is the first to evaluate the effects of solarization on potato cultivars with differing resistance to *V. dahliae*. The increase in yield, even with the highly resistant potato clone (A68113-4) suggests the occurrence of an increased growth response previously described by Katan (3,17,18). However, because nitrogen was not a limiting factor in this study, and because the soil concentrations of P, K, S, Zn, Fe, and B were not different among treatments, nutritional effects to explain an increased growth response were not apparent. Katan (*personal communication*) recently found that increases of fulvic acid in solarized soil may produce beneficial effects on plant growth.

Although an increased growth response may have accounted for a portion of the yield responses, the majority of the benefits were associated with control of Verticillium wilt. Correlation of colonization of *V. dahliae* in potato stems with wilt and yield suggest that *V. dahliae* is the primary factor related to yield responses. The fact that significant yield differences did not occur early in the growing season strengthens this viewpoint. Inoculum densities of *V. dahliae* as low as 10 cfu/g of air-dried soil produced measurable levels of Verticillium wilt and substantial yield reductions. These results are in close agreement with those of Nnodu and Harrison (23) who also estimated the threshold of ID of *V. dahliae* for wilt development to be low (18–23 cfu/g of air-dried soil).

The effects of solarization on other diseases including *R. solani* are well documented (14,26,27). The present study is the first to demonstrate the suppression of common scab of potato by solarization.

TABLE 7. Interaction relationships between 1980 solarization treatment and 1981 cropping history on populations of *Verticillium dahliae* in 1982

Potato genotypes in 1981	*V. dahliae* cfu/g of soil[w,x]		$\log_{10}(n+1)$ *V. dahliae* cfu/g of apical stem tissue[y]	
	Nonsolarized	Solarized	Nonsolarized	Solarized
NDA8694-3	15.3	8.0	3.37 b[z]	3.01 b[z]
Russet Burbank	13.3	7.3	2.74 a	2.97 b
A68113-4	13.3	2.7	2.88 a	1.88 a

[w] From upper 23 cm of soil profiles.

[x] Interaction relationships between solarization treatment and cropping histories were not significant.

[y] Stems for assays were collected 26 Aug (30 stems per plot) from uppermost 7.5 cm.

[z] Different letters arranged vertically indicate significant differences at $P = 0.05$. For horizontal comparisons between solarization treatment and nonsolarization, the LSD value at $P = 0.05$ was 0.46.

Indirect evidence is also provided to substantiate the importance of *V. dahliae* on the yield reduction of the Russet Burbank potato cultivar. A 5-yr study, which compared the continuous cropping of Russet Burbank with the Verticillium wilt resistant A68113-4 (9), indicated that the resistant potato consistently outyielded the Verticillium-susceptible Russet Burbank by 38–142%. In this study, the yields between Russet Burbank and A68113-4 did not differ significantly when *V. dahliae* was suppressed by solarization. In contrast, in the same field, when the disease was not controlled by solarization, A68113-4 significantly outyielded Russet Burbank by 22–31%.

Long-term interaction effects by A68113-4 on ID of *V. dahliae* also occurred during the second crop year after solarization. Potato clone A68113-4 significantly delayed the increase of *V. dahliae*. These results were similar to those previously observed with Acala cotton *Gossypium hirsutum* L. (a resistant cultivar) on reinfestation by *Fusarium* sp. (19).

This work demonstrates the potential for controlling *V. dahliae* in cooler regions by solarization. However, generalization to other diseases should not be made at this stage. The consistent yield responses that were observed in this solarization study indicate that the yield benefits can be substantially greater than the cost of treatment. Thus, soil solarization may have potential commercial value for potato production, especially when the benefit of solarization extends for more than one season.

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