Assessment of Irrigation as a Method of Managing Potato Early Dying

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ABSTRACT

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Pre- and posttuber initiation irrigation treatments were evaluated for their impact on development of potato early dying symptoms in Russet Burbank potatoes grown in field microplots in northcentral Oregon. Irrigation treatments were in a factorial arrangement of three pre- and three posttuber initiation regimes across six inoculum densities of *Verticillium dahliae*. Microplots were drip-irrigated to provide deficit, moderate, or excessive amounts of irrigation water prior to tuber initiation, followed by all nine possible posttuber initiation combinations. Moderate irrigation was approximately equal to estimated consumptive use (ECU) by the plant; the deficit and excessive regimes were 50 and 150% of ECU, respectively. Differences in area under the senescence progress curve (AUSPC) values were significant ($P \leq 0.01$) based on irrigation treatment prior to tuber initiation, whereas posttuber initiation irrigation and the interaction of pre- and posttuber initiation irrigation treatments were not significant. When plants were watered in excess of ECU prior to tuber initiation, AUSPC values were 22% higher than the deficit pretuberization treatment, regardless of the posttuber initiation treatment. Averaged across the nine irrigation treatments, AUSPC values were 2.5 times greater in soils infested with 30 cfu of *V. dahliae* per gram of soil than in noninfested soil. Pretuber initiation irrigation also was assessed as a method of managing potato early dying in cultivar Russet Burbank in field plots in eastern Washington and central Wisconsin. Plots were noninfested or infested with 5 and 25 or 50 cfu of *V. dahliae* per gram of soil. Differential irrigation treatments (deficit, moderate, or excessive) were imposed from plant emergence to tuber initiation (3–5 wk). AUSPC values were significantly lower in the deficit compared to the excessive irrigation treatment. Increases in symptoms of potato early dying were most apparent 850 degree days after planting, when plant senescence exceeded 40%. Senescence was twice as great in infested plots as in noninfested plots. The effect of pretuber initiation irrigation on total tuber yield was inconsistent. In Washington in 1991, tuber yield was significantly ($P \leq 0.05$) greater in the deficit compared to the excessive pretuber initiation treatment. In 1992, there was no effect of irrigation regime on total tuber yield. In Wisconsin, tuber yield was significantly ($P \leq 0.05$) lower in the deficit compared to the moderate or excessive pretuber initiation irrigation regimes. Total tuber yield was significantly ($P \leq 0.05$) reduced as inoculum density was increased. Early season irrigation management may be a viable option to minimize losses due to potato early dying in some production areas.

Additional keywords: cultural practices, soil water pressure, *Solanum tuberosum*, Verticillium wilt.

Potato early dying is a major constraint to potato (*Solanum tuberosum* L.) production in many areas of the United States. This syndrome can be caused by a complex of interacting pathogens but is most often caused by the soilborne fungus *Verticillium dahliae* Kleb. (3,22,25). Soil fumigation, crop rotation, and resistant cultivars are considered management strategies for the suppression of potato early dying. Soil fumigation, however, may be restricted in the near future (16). Crop rotation is not economically practical because microsclerotia of *V. dahliae* survive for long periods of time (>8 yr) in soil in the absence of a susceptible host (14). Few cultivars resistant to *V. dahliae* are acceptable to the industry (17).

The development of potato early dying is influenced by environmental factors such as temperature and water. Increased air temperatures lowered the yield from infected plants in potato early dying studies in Ohio and Minnesota (10,12). Similarly, an increase in soil water was related to an increase in the severity of potato early dying (4), and this syndrome was particularly severe in irrigated regions (21). In a two-location irrigation study using three season-long irrigation regimes, potato early dying was more severe with excessive than with moderate or deficit irrigation (4).

In arid regions, method of irrigation, frequency of irrigation, and soil water content can be controlled. In general, irrigation recommendations emphasize efficient use of water and maximization of yields but do not consider disease control. In studies with citrus (9) and tomato (19), Phytophthora root rot was more severe when the soil was kept wet by prolonged or frequent irrigations compared to conditions that allowed the soil to dry out. Tomato plants infected with *Phytophthora parasitica* during a prolonged irrigation treatment, partitioned less total dry matter into leaves and fruit and more into stems compared to noninfected plants (20). Irrigation practices designed to suppress disease, however, should not compromise crop yield, maturity, or quality. In potato, modifications in irrigation practices for disease suppression must occur prior to tuber initiation to reduce the chance of malformed tubers. The period between plant emergence and tuber initiation is approximately 3–5 wk.

The objectives of our study were to determine the impact of pre- and posttuberization irrigation differentials on symptom expression of potato early dying and to evaluate the effect of pretuber initiation irrigation regimes on severity of potato early dying and associated tuber yield in large field plots.

MATERIALS AND METHODS

Microplot experiment. Microplots were established in 1991 at the Hermiston Agricultural Research and Extension Center in northcentral Oregon (elevation 192 m; 150-day growing season; Quincy fine sandy loam). Factors included nine irrigation treatments and six inoculum densities of *V. dahliae*. A randomized split-plot design with five blocks was used. The main plot was irrigation treatment (row), and inoculum density was the subplot (pot). Three repetitions of each inoculum density were randomized within each row of 18 microplots. There were 15 microplots for each treatment combination and a total of 810 microplots for the experiment.

Microsclerotia of three pathogenic isolates of *V. dahliae* were produced on modified minimal agar (18) overlain with sterile, uncoated cellophane as previously described (4). After 3 wk of growth, microsclerotia were harvested and washed several times on a 38-μm sieve. Concentrated microsclerotia were mixed in a 10-L twin-shell blender with small quantities of fumigated soil to infest soil used in the microplots.

Soil at the study site was fumigated during October 1990 with methyl bromide/chloropicrin (3:2, v/v) at 488 kg/ha to reduce populations of preexisting *V. dahliae* and other pathogens. The fumigant was injected at a depth of 20 cm under a 2.1-m-wide continuous plastic tarpaulin. The tarpaulin remained in place throughout the winter and was removed 1 mo before infesting the soil. Fumigated soil and enough inoculum of *V. dahliae* to produce final inoculum densities of 0, 1, 3, 5, 15, or 30 cfu/g of soil were mixed in a cement mixer for 3 min. Each batch contained enough soil to fill three plastic pots (23-L, 40 cm high × 30 cm outside diameter). Microplots were installed during April 1991 using the methods previously described (4).

Nuclear seed potatoes of *S. tuberosum* cv. Russet Burbank, obtained from the Oregon Foundation Seed Potato Program, Oregon State University, Corvallis, were cut into single-eye seed pieces with a 2.5-cm melon scoop. Seed pieces were presprouted for 2 wk in moist vermiculite at 22 C. A presprouted seed piece was planted 8 cm deep in the center of each pot during the second week of April.

Prior to planting, a drip-irrigation line was established for each row of 18 microplots with a separate irrigation treatment. All microplots were watered to near field capacity before planting. Three initial irrigation treatments were imposed from plant emergence (95% emergence) to tuber initiation, a period of 4–5 wk (deficit, moderate, and excessive). After tuber initiation, the deficit, moderate, and excessive irrigation treatments were nested within each pretuber initiation irrigation treatment that resulted in nine combinations of pre- and posttuber initiation irrigation (deficit-deficit, deficit-moderate, deficit-excessive, moderate-deficit, moderate-moderate, moderate-excessive, excessive-deficit, excessive-moderate, excessive-excessive). Estimated consumptive use (ECU) of water by the plants was obtained by multiplying evapotranspiration (ET), calculated by the Penman equation (11), by crop coefficients for potato (27). Irrigation treatments were designed so the moderate level was approximately equal to ECU. Deficit and excessive irrigation treatments were 50 and 150% of ECU, respectively. These levels were achieved by altering the amount of applied water relative to the moderate level. For example, if plants in the moderate treatment were watered daily, plants in the deficit or excessive treatment were watered every other day or three times in 2 days, respectively. Cumulative net water status (irrigation + rainfall − ECU) for deficit, moderate, and excessive irrigation treatments is illustrated in Figure 1.

Tensiometers (IRROMETER, Soil Moisture, Inc., Riverside, CA) were installed at plant emergence in all noninfested microplots in the deficit-deficit, moderate-moderate, and excessive-excessive water treatments, for a total of 45 tensiometers. Tensiometers were read each morning, beginning with the first irrigation treatment, to monitor soil water pressure in each treatment.

Beginning at tuber initiation (19 June) and continuing at 2-wk intervals, a urea-ammonium nitrate solution (32-0-0) was applied with a syringe to the soil surface directly beneath the drip emitter in each microplot at a rate of 67 kg of N per hectare per application for a total of 268 kg of N/ha (four applications). Microplots were irrigated immediately after fertilization to simulate application of nitrogen through irrigation water. Weeds were removed by hand within and around the microplots. Beginning in early July, plants were rated weekly for percent stems with senescent (chlorotic or necrotic) foliage. Responses of area under the senescence progress curve (AUSPC) (24) were analyzed by the general linear models (GLM) procedure (PROC GLM, [23]). Additionally, plant senescence over time was considered by repeated measures analysis. Degree days after planting (DDAP, base = 12.8 C) were calculated by the methods of Baskerville and Emin (1). There was little variation between repetitions within subplots, so the analysis was done on the averages over repetitions within subplots ($n = 270$).

Field experiments. Field plots were established during 1991 and 1992 at AgriNorthwest, Inc., Plymouth, WA, and during 1991 at the Hancock Experiment Station, Hancock, WI. At both locations, soil was fumigated with metham sodium (194 L/ha) during the fall prior to the field season. The fumigant was applied through the irrigation system. Individual plots were 4.6 × 9.2 m in Washington and 4.6 × 4.6 m in Wisconsin. In Washington, three pretuber initiation irrigation regimes and three inoculum densities of *V. dahliae* were arranged in a split-plot design. Irrigation treatment was the main-plot, and inoculum density was the subplot. Irrigation was applied by overhead sprinkler. There were six replications of each treatment. In Wisconsin, the 3 × 3 factorial combination of treatments was arranged in a randomized complete block design with five replications.

Three isolates of *V. dahliae* were grown on sterile rye grain for 6 wk. The colonized rye seed was air-dried and ground in a Wiley mill. The ground rye was diluted with sterile sand and assayed for *V. dahliae* with the Anderson air sampler (13) or by dilution plating on NP10 medium (26). This inoculum was incorporated to a depth of 15 cm in the field plots to give approximately 0, 5, and 25, or 0, 5, and 50 cfu of *V. dahliae* per gram of soil in 1991 and 1992, respectively.

In Washington, inoculum was incorporated in the soil of four center rows of six-row plots as the rows were opened. Hand-cut seed pieces of cv. Russet Burbank (60 g) were dusted with 2.5% thiophanate methyl (10 g/kg) and hand-planted at 24-cm intervals in rows 90 cm apart. Planting dates were 4 and 6 April 1991 and 1992, respectively. In Wisconsin, the center two rows of four-row plots were infested with inoculum of *V. dahliae*. Inoculum was incorporated into the top 15 cm of soil with a rototiller. Immediately after incorporating the inoculum, five 15-cm soil cores were collected from each plot. Soil samples were

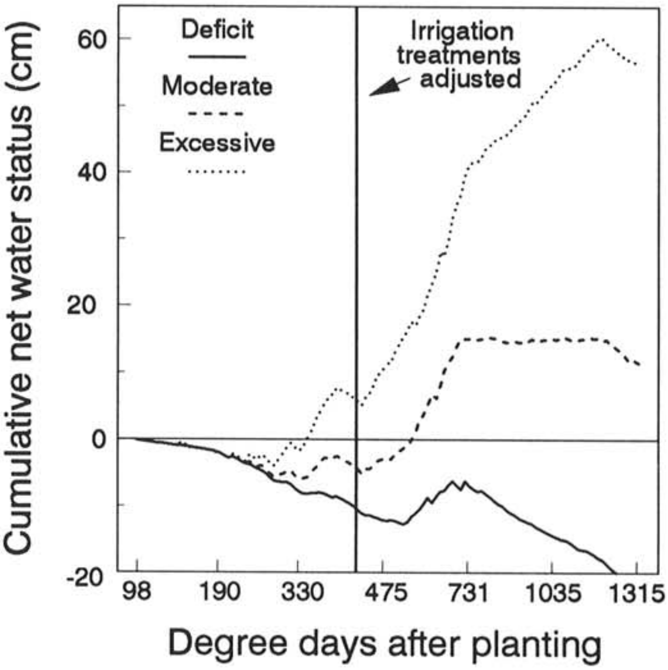

Fig. 1. Cumulative net water status (irrigation + rainfall − estimated consumptive use [ECU]) for Russet Burbank potatoes grown in field microplots under three irrigation treatments in Oregon, 1991. Vertical line indicates the time irrigation treatments were adjusted. All nine irrigation treatments may be visualized by following any two line segments before and after the vertical line, e.g., ——- - - = deficit-moderate. Irrigation treatments were 50, 100, and 150% ECU for deficit, moderate, and excessive treatments, respectively.

air-dried for 2 wk and assayed for *V. dahliae* as described above for the inoculum. Potatoes were hand-planted on 2 May 1991.

In Washington in 1991, five tensiometers were placed 15 cm deep in one replicate of each irrigation treatment. Tensiometer readings were recorded each morning beginning at plant emergence. In 1992, volumetric soil water content was monitored daily by time domain reflectometry (Soil Moisture Corp., Goleta, CA). Ten readings were taken during morning hours from plots representing the three irrigation treatments. In Wisconsin, soil moisture was determined gravimetrically by taking five to six cores at random at a depth of 0–15 cm from the plots, beginning with initiation of the differential irrigation treatments and ending when the irrigation differential stopped (28 May to 3 July). Moisture determinations were made 5 days/wk. Because different techniques were used to measure soil water status, water release curves were used to express these values in common scales. For the Washington data, the water release curve was described by plotting a smooth curve through soil water contents measured at −0.01, −0.033, −0.080, and −0.20 MPa. For the Wisconsin data, the relationship between soil water pressure and volumetric water content was based on a water release curve previously published (2).

Irrigation treatments were imposed from plant emergence to tuber initiation (198–425, 127–347, and 274–490 DDAP for Washington [1991 and 1992] and Wisconsin [1991], respectively) and designed to provide deficit, moderate, or excessive soil water relative to the ECU of the potato plant. Cumulative net water status (irrigation + rainfall − ECU) for deficit, moderate, and excessive irrigation treatments is illustrated in Figure 2.

In Washington in 1991, plots received a preplant dry granular fertilizer containing N, P, K, S, Mg, B, Zn, and Mn at 42.4, 181.5, 32.5, 60.5, 30.2, 1.2, 12.1, and 18.2 kg/ha, respectively. During the growing season, applications of N, P, K, and S through the irrigation system totaled 231.1, 166.9, 72.6, and 42.4 kg/ha, respectively. Fertilizer applications were made weekly. One application of a preemergent insecticide and one of herbicides was made during early May. Dithionate was applied at 24.2 kg/ha for wireworm control, and metribuzin and pendimethalin were applied at 0.7 and 2.4 kg/ha, respectively, for weed control. In 1992, a preplant dry granular fertilizer was applied containing N, P, K, S, Mg, B, Cu, Zn, and Mn at 78.5, 112.1, 280.2, 44.8, 28.0, 2.2, 11.2, 11.2, and 11.2, respectively. For the remainder of the growing season, supplemental fertilizer applications of N, P, and S totaled 289.2, 257.8, and 33.6 kg/ha, respectively. Fertilizers were applied through the irrigation system on a weekly basis. A preemergent herbicide consisting of metribuzin and pendimethalin at 0.7 and 2.4 kg/ha, respectively, was applied.

Petioles from the 1991 Washington study were sampled for nutrient analysis. The fifth petiole from the top of the plant was collected on 19 June and 9 and 29 July. Samples consisting of 25 petioles were collected from each of four replications of the

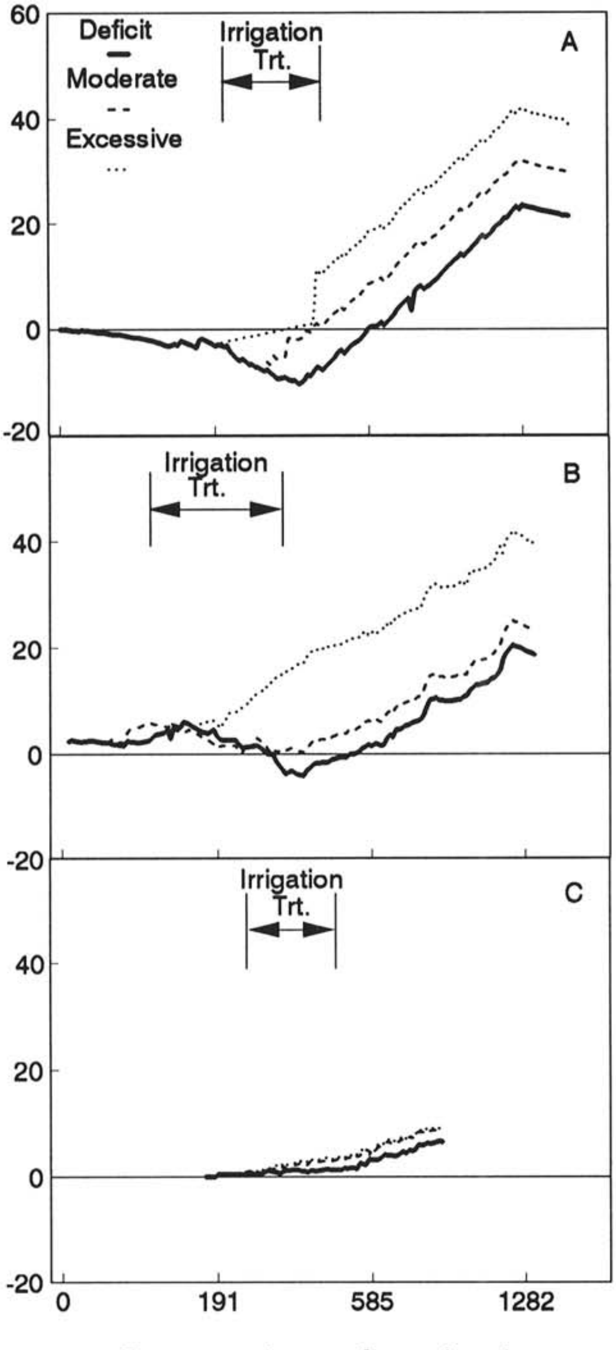

Fig. 2. Cumulative net water status (irrigation + rainfall − estimated consumptive use [ECU]) for Russet Burbank potatoes grown in field plots under three irrigation treatments in **A**, Washington, 1991; **B**, Washington, 1992; and **C**, Wisconsin, 1991. Irrigation treatments were 50, 100, and 150% ECU for deficit, moderate, and excessive treatments, respectively. Two-headed arrows indicate the irrigation treatment period.

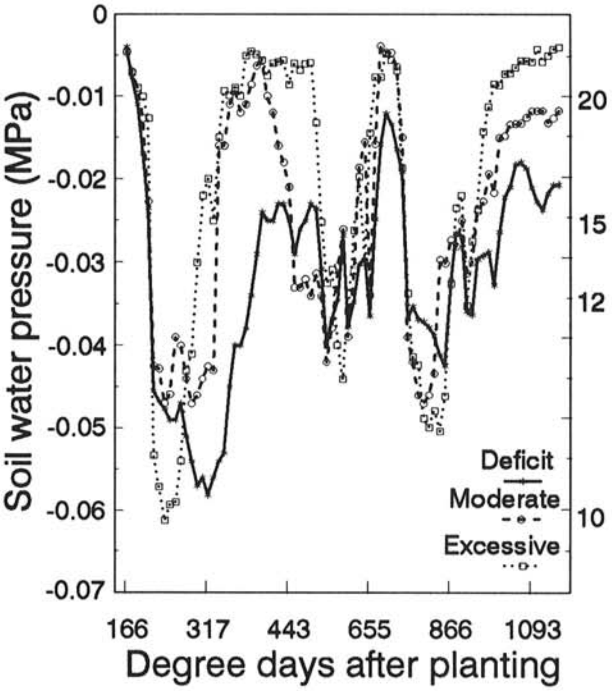

Fig. 3. Soil water pressure in field microplots of Russet Burbank potatoes grown under three season-long irrigation treatments in Oregon, 1991. Each point is the average of 15 tensiometer readings. Tensiometers were placed in pots filled with noninfested soil to a depth of 15 cm. Right y-axis represents percent volumetric water content of soils based on a water release curve.

deficit and excessive irrigation treatments at *V. dahliae* inoculum densities of 0 and 25 cfu/g. Petiole samples were analyzed for nitrate nitrogen by the Plant Analysis Laboratory, Department of Crop and Soil Science, Oregon State University, Corvallis. Interpretation of results was based on critical nutrient ranges established for potatoes in the Pacific Northwest (8).

Beginning in early July in Washington, plants were rated weekly for percent stems with senescent (chlorotic or necrotic) foliage. In Wisconsin, plants were rated weekly beginning in mid-August on a similar scale for percent defoliation. During September, at both locations, the center two rows of each plot were machine dug. Tubers were sorted by size class, weighed, and graded (Washington [1992] and Wisconsin [1991]).

Responses of AUSPC (Washington), area under the defoliation progress curve (AUDPC) (Wisconsin) (24), and tuber yield and grade were analyzed by SAS, version 6.04, PROC GLM (23). Means were separated by Fisher's protected least significant difference (LSD) test. DDAP (base = 12.8 C) was calculated by the methods of Baskerville and Emin (1). Washington data were subjected to the repeated measures analysis by the REPEAT statement in PROC GLM (23) with percent senescence as the response and time as the repeated measure within plots. For Wisconsin, percent defoliation was analyzed separately for each disease-assessment date.

RESULTS

Microplot experiment. Pretuber initiation irrigation treatments were imposed from 161 to 390 DDAP and posttuber initiation irrigation treatments from 391 DDAP through the end of the season. Soil water pressure in the excessive treatment generally ranged between −0.005 and −0.049 MPa, whereas in the deficit irrigation treatment soil water pressure generally ranged between −0.012 and −0.041 Mpa (Fig. 3).

Severity of potato early dying, as measured by AUSPC, was significantly ($P \leq 0.014$) affected by both main effects, irrigation, and inoculum density, but there was no significant irrigation-inoculum interaction. Averaged across inoculum densities, irrigation treatment prior to tuber initiation significantly affected AUSPC, but the posttuber initiation irrigation treatment and the interaction of the pre- and posttuber initiation irrigation treatments were not significant. When plants were watered in excess of ECU prior to tuber initiation, AUSPC values were 22% higher than in the deficit pretuber initiation irrigation treatment, regardless of the posttuber initiation irrigation treatment. Based

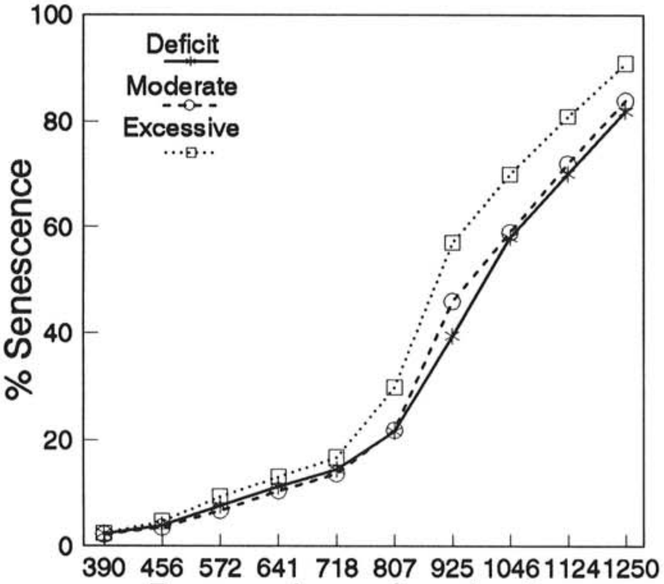

Fig. 4. Senescence progress curves for Russet Burbank potatoes grown in soil noninfested or infested with *Verticillium dahliae* under three irrigation treatments in field microplots in Oregon, 1991. Data are from deficit, moderate, or excessive pretuber initiation irrigation treatments averaged over posttuber initiation irrigation treatments. Each datum point is the mean of 90 observations. Deficit, moderate, and excessive irrigation treatments were 50, 100, and 150% estimated consumptive use, respectively.

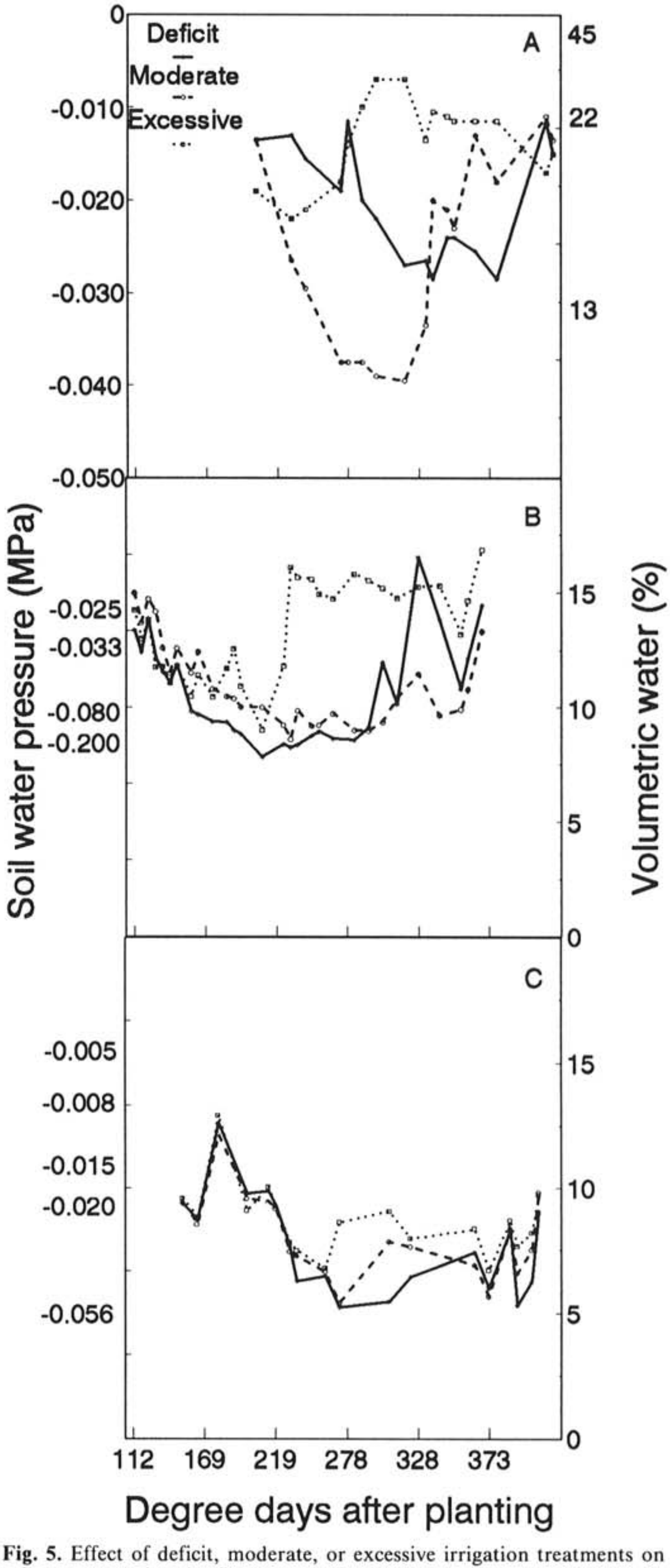

Fig. 5. Effect of deficit, moderate, or excessive irrigation treatments on soil water tension in field plots of Russet Burbank potatoes in **A**, Washington, 1991; **B**, Washington, 1992; and **C**, Wisconsin, 1991. Irrigation treatments were applied from emergence to tuber initiation by overhead sprinklers. Each datum point is the average of five tensiometer readings (soil water pressure) in Washington, 1991; 10 time domain reflectometry readings (volumetric water content) in Washington, 1992; and five gravimetric readings (volumetric water content) in Wisconsin, 1991.

on repeated measures analysis, senescence of foliage in the excessive pretuber initiation irrigation treatment significantly ($P \leq 0.05$) exceeded the moderate or deficit irrigation treatment beginning 807 DDAP through the end of the season (Fig. 4). Averaged across the nine irrigation treatments, AUSPC values were 2.5 times greater in soils infested with 30 cfu of *V. dahliae* per gram of soil than in noninfested soil.

Field plot experiment. In Washington, *V. dahliae* was recovered from soil after initial infestation (*V. dahliae* at 0, 5, and 25 [1991] or 0, 5, and 50 [1992] cfu/g of soil) at 5, 6, and 11 or 4, 14, and 76 cfu/g of soil in 1991 and 1992, respectively. In Wisconsin, recovery rates were 0.1, 4.5, and 21.5 cfu/g of soil for soil initially infested with 0, 5, and 25 cfu/g of soil.

In both Washington and Wisconsin, soil moisture was higher in the excessive compared to the moderate or deficit irrigated plots during most of the treatment period. Soil water pressures ranged from −0.012 to −0.028, −0.013 to −0.040, and −0.007 to −0.021 MPa for the deficit, moderate, and excessive irrigation treatments, respectively, during the treatment period (198–425 DDAP) in Washington (1991; Fig. 5A). Soil water pressure averaged −0.010 MPa after the termination of the irrigation treatments (data not shown). In 1992, percent soil moisture averaged 8, 12, and 16% for the deficit, moderate, and excessive irrigation treatments, respectively, during the treatment period (127–347 DDAP) (Fig. 5B). After the treatment period, soil moisture ranged between 14 and 20% (data not shown). In Wisconsin, soil moisture for all three irrigation treatments was similar up through 270 DDAP. From 274 DDAP through the end of the treatment period (490 DDAP), percent soil moisture averaged 6.6, 7.3, and 8.3% for the deficit, moderate, and excessive irrigation treatments, respectively (Fig. 5C).

In 1991, rate of senescence of potato foliage was significantly ($P \leq 0.05$) affected by both irrigation regime and inoculum density in Washington and Wisconsin. There was no significant irrigation-inoculum interaction. In Washington, AUSPC values were significantly ($P \leq 0.05$) greater in plots irrigated in excess of ECU than in plots receiving the deficit irrigation. Repeated measures analysis revealed that disease severity in the excessive irrigation treatment was significantly greater than in the moderate or deficit treatments from 1,093 DDAP to the end of the season (Fig. 6A).

In Washington in 1992, there was no significant effect of irrigation treatment on AUSPC. When percent senescence was analyzed by repeated measures, however, it was lower in the excessive treatment until 857 DDAP, at which time the rate of plant senescence was accelerated in the excessive treatment, resulting in significantly ($P \leq 0.05$) more senescence than in the deficit and moderate treatments through the end of the season (Fig. 6B). In Wisconsin in 1991, AUDPC values were 302, 383, and 461 for the deficit, moderate, and excessive irrigation regimes, respectively. On the first and third disease-assessment dates, percent defoliation was significantly ($P \leq 0.05$) greater in the excessive irrigation treatment when compared to the moderate or deficit irrigation regimes (Fig. 6C).

Rate of senescence of potato foliage was influenced by inoculum density at both locations. In Washington in 1991, AUSPC values were significantly ($P \leq 0.05$) higher in plots infested with 25 cfu of *V. dahliae* per gram of soil compared to plots noninfested with *V. dahliae*. AUSPC values in plots infested with 25 cfu of *V. dahliae* per gram of soil were 6% higher when compared to noninfested plots. In 1992, AUSPC values were twice as high in plots infested with 50 cfu of *V. dahliae* per gram of soil compared to noninfested plots. In Wisconsin, percent defoliation was significantly ($P \leq 0.05$) greater in plots infested with 25 cfu of *V. dahliae* per gram of soil compared to plots infested with 0 or 5 cfu of *V. dahliae* per gram of soil on all three assessment dates. AUDPC values were 143, 390, and 612 for the soil inoculum densities of 0, 5, and 25 cfu of *V. dahliae* per gram, respectively.

In Washington in 1991, tuber yield was affected by irrigation regime ($P = 0.06$) and inoculum density ($P \leq 0.05$). Total tuber yield was 17% higher in the deficit compared to the excessive irrigation treatment. In the excessive irrigation treatment, tuber yields were significantly higher ($P \leq 0.05$) in weight class 1 and significantly lower in weight class 6 when compared to the deficit or moderate irrigation treatment (Table 1). There was no effect of irrigation treatment on weight class 4, which represents optimum tuber size. Total tuber yield was reduced by 22% in plots infested with 25 cfu of *V.dahliae* per gram of soil compared to those infested with 0 or 5 cfu of *V. dahliae* per gram of soil. This reduction in tuber yield occurred in weight classes 2–4 and 6.

In 1992 in Washington, neither total tuber yield nor weight class was significantly affected by irrigation regime; however, both were influenced by inoculum density ($P \leq 0.05$). Despite the lack of a significant effect of irrigation, tuber yield was 10–28% higher in plots irrigated in excess of ECU compared to the moderate

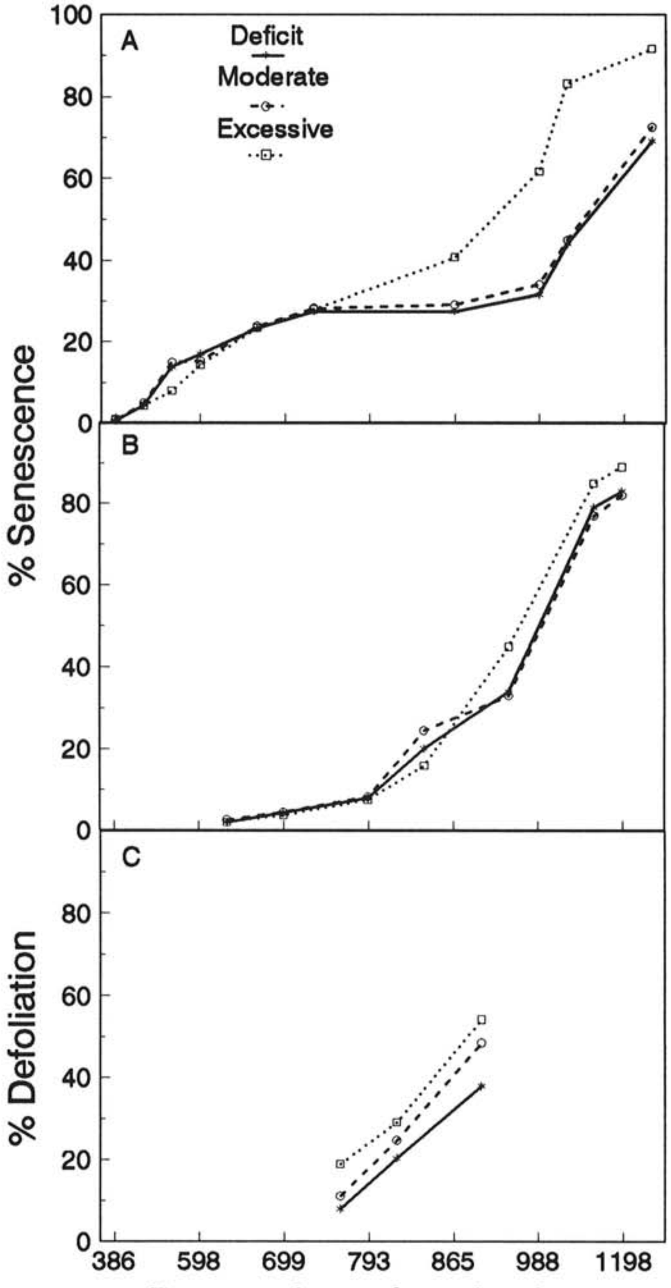

Fig. 6. Senescence (**A and B**) or defoliation (**C**) progress curves for Russet Burbank potatoes grown in soil noninfested or infested with *Verticillium dahliae* under three irrigation treatments in field plots in **A,** Washington, 1991; **B,** Washington, 1992; and **C,** Wisconsin, 1991. Data are for deficit, moderate, or excessive irrigation treatments, which are below, equal to, or above the estimated consumptive use of the potato plant, respectively. Treatment period is from plant emergence to tuber initiation, 198–425, 127–347, and 274–490 degree days after planting in Washington, 1991; Washington, 1992; and Wisconsin, 1991, respectively.

TABLE 1. Effect of irrigation treatment and inoculum density of *Verticillium dahliae* on tuber (T) yield of Russet Burbank potatoes in field plots in Washington, 1991

	Total yield (T/ha)	Weight class[u,v]					
		1	2	3	4[w]	5	6
Irrigation treatment[x]							
Deficit	61.9	5.7 a	7.7	21.5	38.1	16.5	10.3 a
Moderate	66.8	5.5 a	7.5	21.2	39.8	18.6	13.9 a
Excessive	52.9	7.1 b	9.4	20.7	33.9	13.2	7.5 a
P value[y]	0.06	0.00	0.07	0.89	0.22	0.09	0.02
Inoculum density[z]							
0	62.4 a	6.1 a	8.4 a	21.3 a	37.9 a	16.6 a	12.3 a
5	68.6 a	6.5 a	8.9 a	23.3 ab	41.2 a	17.9 a	11.9 a
25	50.7 b	5.6 a	7.4 b	18.8 b	32.7 b	13.9 a	7.9 b
P value	0.00	0.05	0.00	0.00	0.00	0.00	0.00

[u] In grams: class 1, 1–113; class 2, 114–170; class 3, 171–284; class 4, 171–397; class 5, 285–397; class 6, >398.

[v] Means followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's protected least significant difference test.

[w] Weight class 4 represents the optimum tuber weight and is sum of weight classes 3 and 5.

[x] Irrigation treatments were applied from plant emergence to tuber initiation. Deficit, moderate, and excessive irrigation treatments are related to the estimated consumptive use by the plant.

[y] Probability of obtaining $F \leq F_{0.05}$.

[z] Plots were infested at a rate of 0, 5, and 25 cfu of *V. dahliae* per gram of soil. Soils were assayed for populations of *V. dahliae*, and recovery rates were 5, 6, and 11 cfu of *V. dahliae* per gram of soil.

TABLE 2. Effect of irrigation treatments and inoculum density of *Verticillium dahliae* on tuber (T) yield and grade (A, B, and cull) of Russet Burbank potatoes in field plots in Washington, 1992

	Total yield (T/ha)	A	Weight class 4 (171–397 g)	B	Cull	Specific gravity
Irrigation treatment[w]						
Deficit	48.9	24.9	21.9	9.4	2.2	1.087
Moderate	56.9	28.8	26.3	11.8	2.4	1.068
Excessive	62.8	30.7	26.5	12.8	2.2	1.067
P value[x]	0.09	0.33	0.08	0.22	0.98	0.56
Inoculum density[y]						
0	63.0 a[z]	30.9 a[z]	28.8 a[z]	14.5 a[z]	2.4 a[z]	1.069
5	55.6 b	28.5 ab	24.5 b	11.6 b	2.2 a	1.066 a[z]
25	49.9 c	25.7 b	21.5 c	8.6 c	2.4 a	1.085 a
P value	0.001	0.01	0.001	0.001	0.82	0.52

[w] Irrigation treatments were applied from plant emergence to tuber initiation. Deficit, moderate, and excessive irrigation treatments are related to the estimated consumptive use by the plant.

[x] Probability of obtaining $F \leq F_{0.05}$.

[y] Plots were infested at a rate of 0, 5, and 25 cfu of *V. dahliae* per gram of soil. Soils were assayed for populations of *V. dahliae*, and recovery rates were 4, 14, and 76 cfu of *V. dahliae* per gram of soil.

[z] Means followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's protected least significant difference test.

TABLE 3. Effect of irrigation treatments and inoculum density of *Verticillium dahliae* on tuber (T) yield and grade (A, B, and cull) of Russet Burbank potatoes in field plots in central Wisconsin, 1991

	Total yield (T/ha)	A	Weight class 4 (171–369 g)	B	Cull	Specific gravity
Irrigation treatment[w]						
Deficit	41.8 a[x]	28.5 a[x]	15.1	9.6 a[x]	3.7	1.074 a[x]
Moderate	45.9 b	33.3 b	16.3	8.5 a	4.0	1.074 a
Excessive	46.3 b	36.4 c	16.3	5.4 b	4.4	1.073 b
P value[y]	0.006	0.0001	0.49	0.0001	0.07	0.01
Inoculum density[z]						
0	49.3 a	38.0 a	20.2 a[x]	7.6	3.6	1.077 a
5	45.1 b	32.3 b	15.0 b	8.3	4.4	1.074 b
25	39.8 c	27.9 c	12.4 c	7.6	4.2	1.073 b
P value	0.0001	0.0001	0.0001	0.70	0.42	0.0001

[w] Irrigation treatments were applied from plant emergence to tuber initiation. Deficit, moderate, and excessive irrigation treatments are related to the estimated consumptive use by the plant.

[x] Means followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's protected least significant difference test.

[y] Probability of obtaining $F \leq F_{0.05}$.

[z] Plots were infested at a rate of 0, 5, and 25 cfu of *V. dahliae* per gram of soil. Soils were assayed for populations of *V. dahliae*, and recovery rates were 0.1, 4.5, and 21.5 cfu of *V. dahliae* per gram of soil.

and deficit irrigation treatments, respectively. This increase in tuber yield was seen across the four grades. Tuber yields were suppressed by 20 and 10% in plots infested with 25 cfu of *V. dahliae* per gram of soil when compared to plots infested with 0 or 5 cfu of *V. dahliae* per gram of soil, respectively. Similar trends were seen across all grades but culls. There was no significant effect of irrigation treatment or inoculum density on specific gravity (Table 2).

In Wisconsin, the total tuber yield was significantly ($P \leq 0.05$) affected by irrigation regime. Total tuber yield was decreased by 10% in deficit compared to excessive irrigation treatment. This reduction was seen in both grade A and B potatoes; there was, however, no effect of irrigation treatment on weight class 4. Specific gravity was significantly lower in the excessive compared to the moderate and deficit irrigation treatments. There was a significant ($P \leq 0.05$) decrease (14%) in total tuber yield in infested soils compared to noninfested soils. Specific gravity was significantly ($P \leq 0.05$) higher in the noninfested compared to the infested plots (Table 3).

In Washington in 1991, mean seasonal nitrate nitrogen concentrations in petioles averaged 2.2 and 2.1% in the deficit and excessive irrigation treatments, respectively. These values were within the critical range for Russet Burbank potatoes.

The amount of water that came as rainfall during the irrigation treatment period varied by location and year. In Washington in 1991, the percentage of water applied during the treatment period that came as rain was 18, 11, and 8% for the deficit, moderate, and excessive irrigation treatments, respectively. In 1992, the percentages were 46, 34, and 18% for the deficit, moderate, and excessive irrigation treatments, respectively. In Wisconsin, 78, 70, and 48% of the applied water came in the form of rain during the differential treatment period for the deficit, moderate, and excessive irrigation treatments, respectively (Fig. 7).

DISCUSSION

Potato early dying is influenced by soil moisture content. In the microplot study, onset of senescence, indicative of potato early dying, was earlier and severity was greater in plants irrigated in excess of ECU prior to tuber initiation. Irrigation treatment after tuber initiation had no effect on rates of foliar senescence. In the large field plots, senescence of potato foliage was enhanced by the excessive pretuber initiation treatment at two geographically diverse locations. Although the irrigation treatments were applied for 3–5 wk beginning at plant emergence, symptoms of potato early dying were not apparent until 6–8 wk after the irrigation treatments had been terminated. As the season progressed, plant senescence was accelerated in those plots that received the excessive irrigation treatment prior to tuber initiation. The consistency of the response to irrigation treatments across locations suggests that altering irrigation practices during the period between emergence and tuber initiation may be a viable option for managing this disease. Differences in the magnitude of these responses between Washington and Wisconsin, however, suggest that environment can have a major impact on the results.

The disparity in severity of potato early dying between Washington and Wisconsin may be attributed to differences in the environment. In 1991, average daily temperatures during tuber bulking were similar (22.3 and 20.7 C in Washington and Wisconsin, respectively), but ET rates differed markedly. In 1991, estimated ET values for Washington and Wisconsin during June, July, and August were 68.6, 86.4, 81.3, and 48.3, 38.1, and 33.0 mm, respectively. ET rates were twice as high in Washington as in Wisconsin during this period, which corresponds to the time when the pathogen colonizes the vascular tissue. High daily ET rate may increase the movement of conidia of *V. dahliae* in the vascular tissue, which would, in turn, affect the rate of plant senescence. The differences in environment between Washington and Wisconsin also can be illustrated by cumulative degree days. In Wisconsin, percent defoliation reached 50% in the excessive irrigation treatment at 900 DDAP (26 August). Disease severity was similar in Washington at 900 DDAP; however, 900 DDAP occurred at midseason (31 July), approximately 4 wk earlier. Thus, climatic conditions in Wisconsin were not as conducive as those in Washington to the development of symptoms of potato early dying.

Though field plots were fumigated prior to the study, inoculum of *V. dahliae* was not completely eliminated from the soil. Low levels (0.1–5 cfu per gram of soil) of *V. dahliae* were recovered from the noninfested soil at each location. This may suggest, in part, why there was no irrigation-inoculum interaction for disease severity in any year (i.e., there was no true control). Thus, plant senescence can be enhanced by excessive early season irrigation or high levels of inoculum; most rapid acceleration of

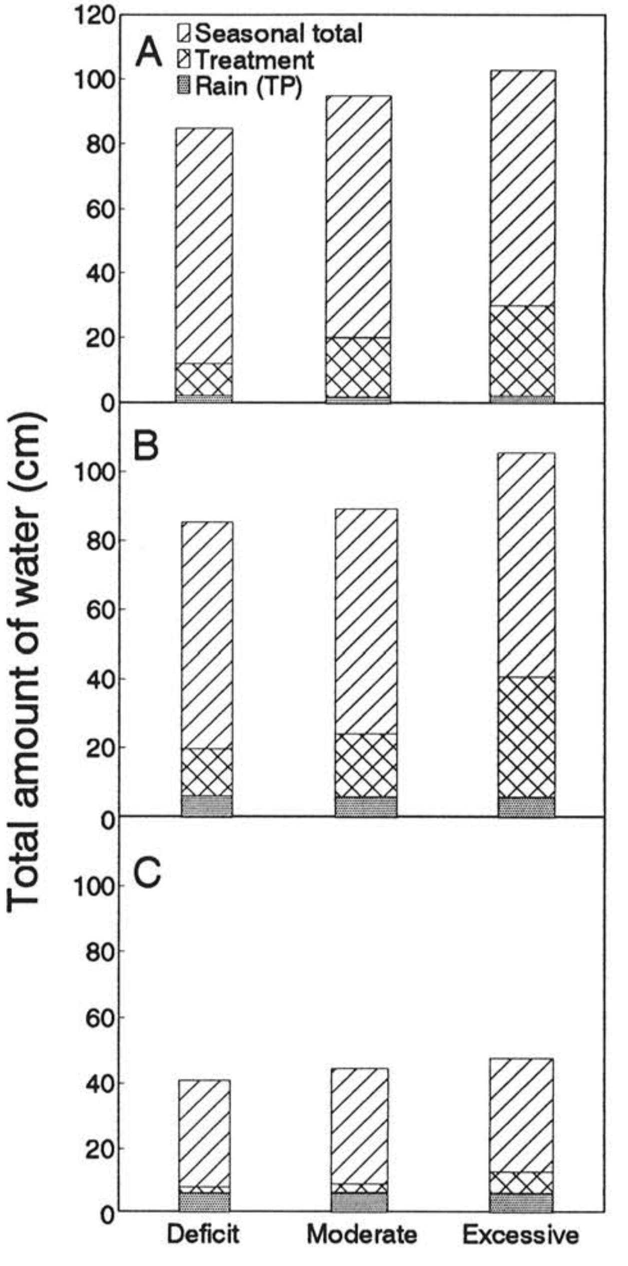

Fig. 7. Amount of total water for irrigation studies on Russet Burbank potatoes in **A,** Washington, 1991; **B,** Washington, 1992; and **C,** Wisconsin, 1991. Treatments are deficit, moderate, or excessive irrigation regimes that are below, equal to, or above the estimated consumptive use of the potato plant, respectively. Treatment period (TP) is from plant emergence to tuber initiation, 425, 347, and 490 degree days after planting in Washington, 1991; Washington, 1992; and Wisconsin, 1991, respectively. Bar segments indicate the total amount of water during the treatment period, the portion of the water that came from rain, and seasonal totals.

plant senescence, however, occurs when both conditions are present—an effect that is additive.

Severity of potato early dying may depend more on the extent of vascular colonization (the rate at which the fungus progresses through the vascular tissue) rather than the number of root infections. Though the rate of colonization of potato stems by *V. dahliae* is related to initial soil populations (15), disease severity is not always correlated with inoculum density in soil (6). Climatic, edaphic, microbiological, and management factors have been suggested as important variables in host response to this disease (6,7,12). Another factor, soil water content, may directly affect the plant's response to disease.

In potato, there are five defined stages of plant growth. The irrigation treatments in this study were imposed from emergence through tuber initiation, which represent vegetative growth stages II and III (22). It is during this second growth stage that the roots and stolons develop (22). The amount of water available to the plant during this vegetative growth stage has a direct effect on plant development. In two greenhouse studies in which potatoes were watered at either a deficit (−0.15 Mpa) or excessive (−0.03 Mpa) soil moisture level, fresh root weight was significantly greater in the deficit compared to the excessive soil moisture treatment (S. M. Gaudreault and M. L. Powelson, *unpublished data*). At the same time, the above ground plant weight was greatest with the excessive soil moisture treatment. Early season moisture promotes above-ground growth, while accelerating the maturation of the plant. These plants have a lower root biomass. As the plant matures, the root biomass never catches up with the aerial biomass. Putting an additional stress on the root tissue may make the plant more vulnerable to successful vascular infections by *V. dahliae*. This imbalance in plant development also may account for the increase in the rate of plant senescence under excessive soil moisture in the absence of disease. By the final assessment date in Washington in 1991, percent senescence in the noninfested plots was 20% greater in the excessive compared to the moderate or deficit pretuberization irrigation treatments.

The effect of pretuber initiation irrigation treatments on total tuber yield was not consistent across sites. The largest increase in disease due to the excessive irrigation treatment occurred in Washington in 1991. This also was the site at which tuber yield was suppressed in the excessive compared to the moderate or deficit irrigation treatment. In contrast, yields were higher in the excessive irrigation treatment in Washington in 1992 and Wisconsin in 1991. Tuber size tended to reflect the same trends as total tuber yield. However, there was no difference in weight class 4 (optimum tuber size) due to irrigation treatment at any site. Differences in tuber yield and grade due to irrigation treatment may be more difficult to detect than differences in disease severity because several factors contribute to the final yield. First, the separation between irrigation treatments for disease severity was much greater in Washington in 1991 than in 1992 or in Wisconsin in 1991. Secondly, due to weather conditions, 1991 was a much better year to impose the irrigation treatments. In Washington in 1992 and in Wisconsin in 1991, a high proportion of water came in the form of rainfall, limiting the flexibility in irrigation decisions. This is seen clearly in net water use (Fig. 2): in Washington in 1992 and Wisconsin in 1991, the cumulative net water status was rarely below zero. Finally, the later onset of senescence coupled with the lower amount of defoliation may explain, in part, why yields were higher in the excessive compared to the deficit or moderate irrigation treatments in Wisconsin.

Irrigation decisions have frequently been driven by environmental indicators and plant-growth models that use accounting approaches to balance water inputs. One such program used successfully in Wisconsin is Potato Crop Management (PCM) (5). Irrigation scheduling is just one component of PCM that uses a season-long approach to water management. In this study, plant senescence was suppressed when soil moisture levels were kept below 100% ECU prior to tuber initiation, whereas the amount of water applied after posttuber initiation appeared to have no effect on rate of plant senescence. The effect of water is most pronounced early in the growth of the crop, a time in the phenology of the crop when the risk of reducing tuber quality and yield from dry soil conditions is at its lowest.

Early season water management may not be suited to all irrigated potato-production areas or every growing season. Irrigation management is most suited to areas and years with a minimal spring rainfall pattern. In this study, we were able to obtain disease suppression by reducing the amount of water applied by 7–9 cm between plant emergence and tuber initiation. Future studies will fine-tune irrigation decisions to maximize disease suppression and maintain optimum yield and grade.

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