Comparative Study of Microclimate and Downy Mildew Development in Subsurface Drip- and Furrow-Irrigated Lettuce Fields in California

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ABSTRACT

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Microclimates and downy mildew (caused by *Bremia lactucae*) disease progress were monitored in neighboring lettuce fields with subsurface drip or furrow irrigation during five trials in 1992 to 1993. The trials included a total of ten irrigation events during which soil moisture, soil temperature, canopy air temperature and humidity, leaf wetness duration, wind speed, and solar radiation were recorded. Disease intensity was assessed at intervals, beginning at thinning of the crop and ending just before harvest. Wilcoxon's Signed Rank Tests were computed to compare microclimates between drip- and furrow-irrigated fields, separately for days before or after irrigation. There were no significant differences in microclimate between the two irrigation methods before irrigation. Within 3 days after irrigation, there were significantly longer overall leaf wetness periods ($P \leq 0.0025$) and a trend toward higher daytime humidity ($P \leq 0.1254$) and longer morning leaf wetness periods ($P \leq 0.0863$) in fields with furrow irrigation. Air temperature and nighttime humidity were not consistently different between the two irrigation methods. Downy mildew developed in four of the five trials, and disease intensity was always lower under drip irrigation than under furrow irrigation. The magnitude of the differences in disease was small, however. It appears that, on most days in coastal California, mesoclimatic variations outweigh microclimatic modifications that could potentially influence disease development.

The effects of irrigation on the development of plant diseases have been investigated actively in most countries in which irrigated agriculture is practiced (10,11, 18). Most studies with foliar pathogens compared overhead- (sprinkler-) and surface- (furrow-) irrigated fields for microclimate and disease development (10,16, 18,20). Usually, more disease was observed under sprinkler irrigation, due to longer leaf wetness durations (LWD), increased canopy air humidity, and/or enhanced dispersal of inoculum by splashing (10,18). These effects were also dependent on the time at which irrigation was applied. For example, Rotem et al. (19) found that the impacts of sprinkler irrigation on microclimate and potato late blight (caused by *Phytophthora infestans*) development under semi-arid conditions are reduced when sprinklers are operated in the afternoon or evening rather than in the morning, probably because sporangia of *P. infestans* are released in the morning and die under adverse conditions later during the day (17).

The effects of different surface irrigation methods on foliar disease development are less well understood. Rotem et al. (18,20), working with potato late blight in Israel, found little difference in microclimate (including LWD) and disease intensity when furrow irrigation was applied at different frequencies (at 7- to 28-day intervals). In similar studies in Nebraska, the amount and frequency of furrow irrigation to field beans greatly influenced white mold (caused by *Sclerotinia sclerotiorum*) development (4,7,8). The authors attributed the increase in disease to the denser canopy that developed under heavy or more frequent irrigation, which resulted in a microclimate more favorable for the disease. One of the few systematic studies in which the effects of drip and furrow irrigation on the development of a foliar disease were compared was carried out by Allen et al. (1) in Australia. They reported that drip irrigation (with irrigation tapes placed on the soil surface or buried at 20 cm depth) decreased or increased bacterial blight (caused by *Xanthomonas campestris* pv. *malvacearum*) on cotton in different experiments and different years, depending on which irrigation method resulted in the most waterlogging and/or the densest canopy.

Our overall research project is directed toward developing management models for downy mildew (caused by *Bremia lactucae* Regel) on lettuce (*Lactuca sativa* L.) in California. For *B. lactucae*, the effects of microclimate (temperature, LWD, and air humidity) on spore germination, infection, and sporulation have been characterized (15,22,26,29). In a previous field study, carried out during 2 years in commercial lettuce fields in coastal California, we found that infection periods for *B. lactucae* occurred chiefly on days on which leaf wetness ended late in the morning (at 1000 h Pacific Standard Time or later), suggesting that fungicide applications could be scheduled according to morning leaf wetness (24). Given the importance of leaf wetness for infection, a procedure to estimate LWD using standard weather data or weather forecasts was developed. A model for leaf wetness caused by dew (14) was adapted for the meteorological conditions of coastal California (23). The model is based on energy budget equations to simulate condensation and evaporation of dew, using air temperature and humidity, cloud cover, and wind speed as input variables. It accounts for downward flux of atmospheric moisture by turbulent transfer, but not for upward distillation of moisture from the soil, which may occur over wet soil during calm nights (6). Before this model can be used as part of a downy mildew disease warning system, it should be determined whether different irrigation methods, which may result in very different soil moisture regimes, influence microclimate (particularly LWD) and disease development in commercial lettuce fields.

Irrigation is indispensable for the production of lettuce in the semiarid environment of California. As a standard horticultural practice, all lettuce fields are sprinkler-irrigated up to 3 weeks after planting to aid seedling emergence and stand establishment. Then, growers often switch to furrow or drip irrigation until the crop is harvested. Furrow-irrigated fields are usually watered at weekly to biweekly intervals with about 5 to 7.5 cm of water during each irrigation event. After irrigation, the soil surface remains wet for at least 3 to 4 days. Subsurface drip-irrigated fields, which currently account for less than 5% of the irrigated hectarage in our study area (K. F. Schulbach, *personal communication*), are usually watered twice per week from irrigation tapes buried at a depth of about 15 cm. Since only small volumes of water (about 1.3 to 2 cm) are applied during each irrigation event, the soil surface remains dry most of the time.

The objective of this research was to determine whether different irrigation methods (subsurface drip versus furrow irrigation) give rise to different microclimates in lettuce fields and, if so, whether these differences influence downy mildew development. A knowledge of such effects could be useful for disease prediction and

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for attempts to control downy mildew through changes in irrigation management.

MATERIALS AND METHODS

Field trials. The studies were carried out in commercial lettuce fields near Salinas (Monterey County) and San Juan Bautista (San Benito County) in California's central coast lettuce production area. The climate at Salinas is influenced by the advection of cool, moist air from the Pacific (Monterey Bay) during the growing season (average diurnal temperature range 8.5/19.6°C). Marine stratus clouds occur frequently, resulting in reduced insolation and low evaporation rates. The climate at San Juan Bautista is characterized by reduced marine advection and an increase in the importance of continental climate features (average diurnal temperature range 6.1/22.0°C). Rain is uncommon at both locations during summer and fall.

At both sites, pairs of fields (one field each with subsurface drip or furrow irrigation) were identified that met the following criteria: both fields located in a level area, surrounded by irrigated farmland, without obstruction to airflow by buildings or trees; distance between paired fields <500 m; both fields planted to the same cultivar, with variation in planting dates not more than 1 week; cultivars susceptible to one or more of the prevalent pathotypes of *B. lactucae* in California (pathotypes IIA, IIB, IIC, IV, and numerous "novel" pathotypes) (12); no fungicides against downy mildew applied to areas of at least 300 m^2 in each field; and similar crop management in both fields, except irrigation. We located five pairs of fields that met these criteria (Table 1). In these fields, lettuce was grown following recommended practices (2). The plant density after thinning was about 32,000 plants per hectare on beds that were 51 cm wide and separated by 50 cm wide and 10 cm deep furrows.

Sampling and data collection. In the areas left untreated with fungicides, canopy air temperature (Ta) and relative humidity (RH) were measured at a height of 15 cm with shielded thermistors and sulfonated polystyrene humidity transducers, respectively (Campbell Scientific Inc., Logan, Utah). The measurements were made with two replicate sensors, located 5 to 20 m apart on the same bed. Vapor pressure (VP) was calculated from measurements of Ta and RH using the equations in Snyder et al. (27). LWD was estimated with two to four electronic leaf wetness sensing grids (Campbell Scientific Inc.) per field. The grids were located between lettuce plants at a height of 10 cm above the soil. They were slightly tipped along their long axes toward the northwest so that they were fully exposed to the sky. Wind speed was monitored above the crop at a height of 40 cm with a cup anemometer (R. M. Young Co., Traverse City, Mich.). Measurements of solar radiation were made with a silicon pyranometer (LI-COR Inc., Lincoln, Nebr.). Soil moisture was recorded using two cylindrical gypsum blocks (Campbell Scientific Inc.) per field, buried at a depth of 5 cm at the edge of the bed. Measurements of soil temperature (Ts) at 10 cm depth were obtained with two water-resistant thermistor probes. All sensor signals were sampled at 5-min intervals with a data logger.

Downy mildew incidence (proportion of plants with at least one lesion) and severity (number of lesions per plant) were recorded at 3- to 21-day intervals, depending on crop age and disease development. Most disease assessments were made at 10-day intervals, beginning at thinning of the crop and ending just before harvest. At least 70 plants per field were examined, but usually several hundred plants were assessed when disease incidence was low or when plants were small (before early rosette growth stage). All fields were sampled following an X-pattern (9) within the area left untreated with fungicides. To summarize downy mildew development, areas under the disease progress curves (AUDPC) were calculated, based on disease incidence. This was done separately for the four "arms" of the X-pattern to obtain subsamples for estimating the within-field variability in disease.

Microclimate data analysis. Three irrigation events, defined hereafter as 6-day periods around the days on which furrow-irrigated fields were watered, occurred on average during each of the five trials. However, only a total of ten irrigation events could be used for data analysis due to interference by rain (during parts of trials 1 and 4) or sensor malfunction (during parts of trial 2). Reliability of microclimate measurements was assured by including only those periods during which readings of replicate sensors within the same field did not differ by more than 5 to 10% for Ts, Ta, and RH. Synoptic weather patterns during the ten irrigation events are listed in Table 2.

For each irrigation event, differences in hourly averages of Ts, Ta, RH, and VP between paired drip- and furrow-irrigated fields were calculated and plotted against time. Positive differences indicated that sensor readings were higher in drip-

Table 1. Aspects of five trials in which microclimate and lettuce downy mildew development were compared in paired fields with subsurface drip and furrow irrigation

Trial	Location	Cropping season	Lettuce cultivar	Soil type
1	San Juan Bautista	Spring 1992	Pybas 251	Sorrento silt loam
2	San Juan Bautista	Summer 1992	Pybas 251	Sorrento silt loam
3	Salinas	Fall 1992	Darkland	Cropley silt clay
4	Salinas	Spring 1993	Amigo	Salinas clay loam
5	Salinas	Fall 1993	Regal	Salinas clay loam

Table 2. Aspects of ten irrigation events used for analyzing microclimates in paired lettuce fields with subsurface drip and furrow irrigation

Trial[a]	Irrigation event[b]	Weeks before harvest	Prevailing weather pattern
1	6 to 12 April 1992	2	High pressure with clear skies and cold nights during first half of the period, followed by a low pressure system and clouds.
	14 to 20 April 1992	1	Gusty offshore winds with above normal temperatures.
2	23 to 29 August 1992	2	Dry and stable airmass, weak onshore flow, clear skies with late night low clouds and above normal temperatures.
3	21 to 27 September 1992	2	Strong high pressure during first half of the period, followed by low pressure system with cooler temperatures.
	28 September to 4 October 1992	1	Cool and dry airmass with dense late night and morning fog.
4	8 to 14 June 1993	1	Fair except for late night and morning low clouds; cool and breezy.
5	17 to 23 September 1993	6	Weak upper level system with mostly cloudy skies and below normal temperatures.
	29 September to 5 October 1993	4	Cool with dense fog and drizzle.
	12 to 18 October 1993	2	Low pressure system with advection of subtropical moisture; dense morning fog and cool temperatures.
	19 to 25 October 1993	1	Low pressure system moved out of the area during the first half of the period, replaced by a high pressure system.

[a] Table 1 explains the trials.
[b] Six-day period around the day on which water was applied to the furrow-irrigated field.

irrigated fields and negative differences corresponded to higher readings in furrow-irrigated fields. Small differences between the two irrigation methods were sometimes observed before irrigation (when fields under both irrigation methods were dry), probably due to more vigorous crop growth in furrow-irrigated fields in some trials or because of slight dissimilarities in sensor calibration. To qualitatively assess the influence of irrigation, comparisons were made between the signs and magnitudes of the differences in microclimate after irrigation relative to the differences before irrigation.

For statistical analysis, hourly averages of Ta, RH, and leaf wetness were summarized for each day, yielding the derived variables maximum temperature (Tmax), minimum temperature (Tmin), numbers of hours with RH ≤ 70% (RH70), numbers of hours with RH ≥ 90% (RH90), and overall LWD. RH70 and RH90 reflected the durations of daytime dry and nighttime humid periods, respectively. Since previous field studies showed infection of lettuce by *B. lactucae* to occur during mornings with prolonged leaf wetness (24), we also recorded the times at which leaf wetness ended for the two irrigation methods (variable name AM-LWD). Wilcoxon's Signed Rank Tests (28) were computed to evaluate the null hypothesis that differences in daily values of Tmax, Tmin, RH70, RH90, LWD, and AM-LWD between drip- and furrow-irrigated fields have a median of zero. The analyses were done separately for days before or after irrigation.

RESULTS

Hourly microclimate. Differences in hourly microclimate between paired fields with subsurface drip and furrow irrigation were apparent during most irrigation events. This is illustrated in Figures 1 and 2 with two irrigation events that occurred during different synoptic weather patterns; these events represent two different classes of microclimate responses to irrigation.

The irrigation event described in Figure 1 was part of trial 2 and occurred from 23 to 29 August 1992. Daytime temperatures were above normal, with clear skies and reduced inflow of marine air. Before irrigation, Ts was lower at night (up to 1.0°C) and slightly higher during the day (up to 0.5°C) in the drip-irrigated field (Fig. 1A).

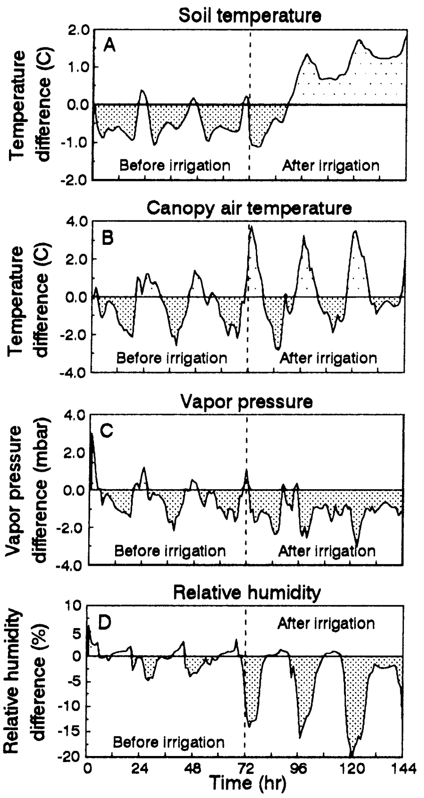

Fig. 1. Hourly differences in **(A)** soil temperature, **(B)** canopy air temperature, **(C)** vapor pressure, and **(D)** relative humidity between paired lettuce fields with subsurface drip and furrow irrigation during one of the irrigation events (trial 2, 23 to 29 August 1992, warm and dry period). Positive differences indicate that values were higher in drip-irrigated fields. Hours 0, 24, 48, ..., 144 = noon; hours 12, 36, 60, ..., 132 = midnight.

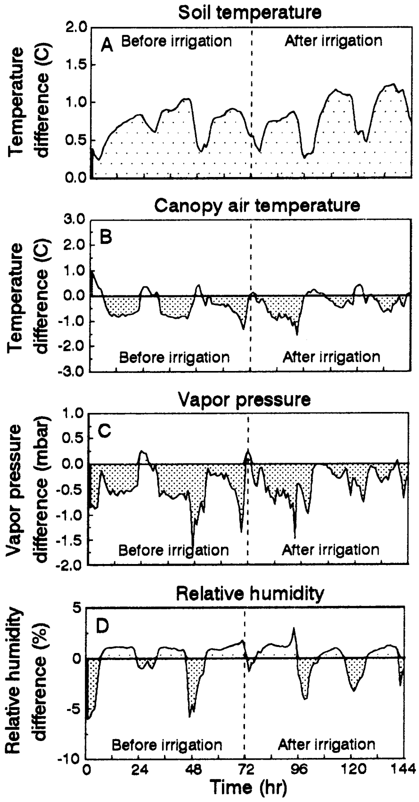

Fig. 2. Hourly differences in **(A)** soil temperature, **(B)** canopy air temperature, **(C)** vapor pressure, and **(D)** relative humidity between paired lettuce fields with subsurface drip and furrow irrigation during one of the irrigation events (trial 5, 12 to 18 October 1993, cool and moist period). Positive differences indicate that values were higher in drip-irrigated fields. Hours 0, 24, 48, ..., 144 = noon; hours 12, 36, 60, ..., 132 = midnight.

This pattern changed after irrigation: Ts in the field with drip irrigation increased relative to the furrow-irrigated field and was consistently higher (up to 2.0°C) toward the end of the period.

Similar to Ts, Ta was lower at night (up to 2.0°C) and higher during the day (up to 1.0°C) in the drip-irrigated field before irrigation (Fig. 1B). Values of daytime Ta were up to 4.0°C higher in the drip-irrigated field after irrigation.

Before irrigation, VP was lower at night (up to 2.0 mbar) and higher at midday (up to 3.0 mbar) in the drip-irrigated field (Fig. 1C). Differences in VP were consistently negative after irrigation, when VP was up to 3.0 mbar lower in the drip-irrigated field.

RH was lower during the day (up to 5.0%) and higher at night (also up to 5.0%) in the drip-irrigated field before irrigation (Fig. 1D). After irrigation, daytime differences increased substantially (RH up to 20% lower in the drip-irrigated field), whereas nighttime differences decreased slightly.

The irrigation event described in Figure 2 was part of trial 5 and occurred from 12 to 18 October 1993. A low pressure system was accompanied by inflow of subtropical moisture during this period. Skies were partly cloudy, with areas of dense morning fog. Daytime temperatures were normal. Before irrigation, Ts and Ta between the fields with drip and furrow irrigation differed by up to 1.0 C (Fig. 2A and B). After irrigation, Ts and Ta in the furrow-irrigated field did not change relative to the drip-irrigated field.

Before irrigation, canopy air humidity (varables VP and RH) was lower in the drip-irrigated field (Fig. 2C and D). This pattern did not change after irrigation, except that differences became progressively smaller.

Daily microclimate. When daily microclimate data from the ten irrigation events were pooled and subjected to Wilcoxon's Rank Test procedure, values of Tmax were found to coincide closely in drip- and furrow-irrigated fields before irrigation (Fig. 3A). This was also true for Tmin (Fig. 3B). The relationships did not change significantly after irrigation.

Values of RH70 (reflecting the durations of dry periods during the day) did not differ significantly before irrigation (Fig. 3C). After irrigation, there was a trend ($P \leq 0.1254$) toward more hours with RH lower than 70% in drip-irrigated fields. RH70 had a median of 6 h in drip-irrigated fields and a median of 4 h in furrow-irrigated fields after irrigation.

Values of RH90 (reflecting the durations of humid periods at night) coincided very closely before irrigation (Fig. 4A), and this pattern remained unchanged after irrigation. There was no statistically significant deviation from a 1:1 relationship, suggesting that furrow irrigation did not influence canopy air humidity at night.

The scatter among the data points for LWD was greater than for other microclimate variables (Fig. 4B). LWD did not differ significantly between the two irrigation methods before irrigation, but there was a weak trend toward longer LWD in furrow-irrigated fields ($P \leq 0.1557$). This may have been due to more vigorous crop growth in furrow-irrigated fields in some trials, which may have resulted in slower evaporation of leaf wetness. After irrigation, LWD was significantly ($P \leq 0.0025$) longer under furrow irrigation. LWD had a median of 9 h in drip-irrigated fields and a median of 12 h in furrow-irrigated fields after irrigation.

LWD in the morning was not significantly different in drip- and furrow-irrigated fields before irrigation (Fig. 4C). After irrigation, there was a trend ($P \leq 0.0863$) for leaves to dry later in the morning in furrow-irrigated than in drip-irrigated fields. The median time at which leaf wetness ended was 0730 h in drip-irrigated fields and 0800 h in furrow-irrigated fields after irrigation.

Disease development. Downy mildew development was very variable in our studies (Table 3). During trial 1, infection occurred early, favored by spring rains after thinning of the crop. This resulted in 100% disease incidence and high values of AUDPC for both irrigation methods. In all other trials, disease developed only shortly before harvest and disease intensities were very low. Disease severity never exceeded one lesion per plant in these trials (data not shown). Downy mildew did not develop during trials 2, 3, and 5 in drip-irrigated fields and during trial 3 in the furrow-irrigated field. In all trials in which infection did occur in at least one of the fields, values of disease incidence and AUDPC were lower under drip irrigation than under furrow irrigation (Table 3). The magnitude of the differences in disease intensity was small, however.

DISCUSSION

Leaf wetness and daytime humidity in lettuce fields are influenced by the method of irrigation. Within 3 days after irrigation, we recorded significantly longer overall wetness periods and a trend toward higher daytime humidity and longer morning wetness periods in furrow-irrigated fields than in subsurface drip-irrigated fields. Air temperature and nighttime humidity did not consistently differ between the two irrigation methods. These results agree in part with previous reports that furrow irrigation of row crops (such as beans or potatoes) significantly reduces daytime air temperature, increases daytime humidity, and shows variable effects on humidity at night and LWD (4,7,8,18,20). Differences between our findings and earlier reports may be due to differences in climate between our study area and other semi-arid regions in which comparable studies were carried out (e.g., Nebraska or Israel). Because of the cold waters off the coast and the persistent marine inversion, nocturnal stratus occurs frequently in the coastal regions of California (5,13). This reduces radiative cooling at night and results in relatively warm and calm nights that favor upward flux (distillation) of moisture from wet (irrigated) soil to the canopy (6). Stratus clouds often do not dissipate before mid-morning or early afternoon so that evaporation rates during the morning remain low. This may explain why significant effects of furrow irrigation on LWD were observed in our study, but not in others that were carried out in drier climates where distillation at night may be weaker

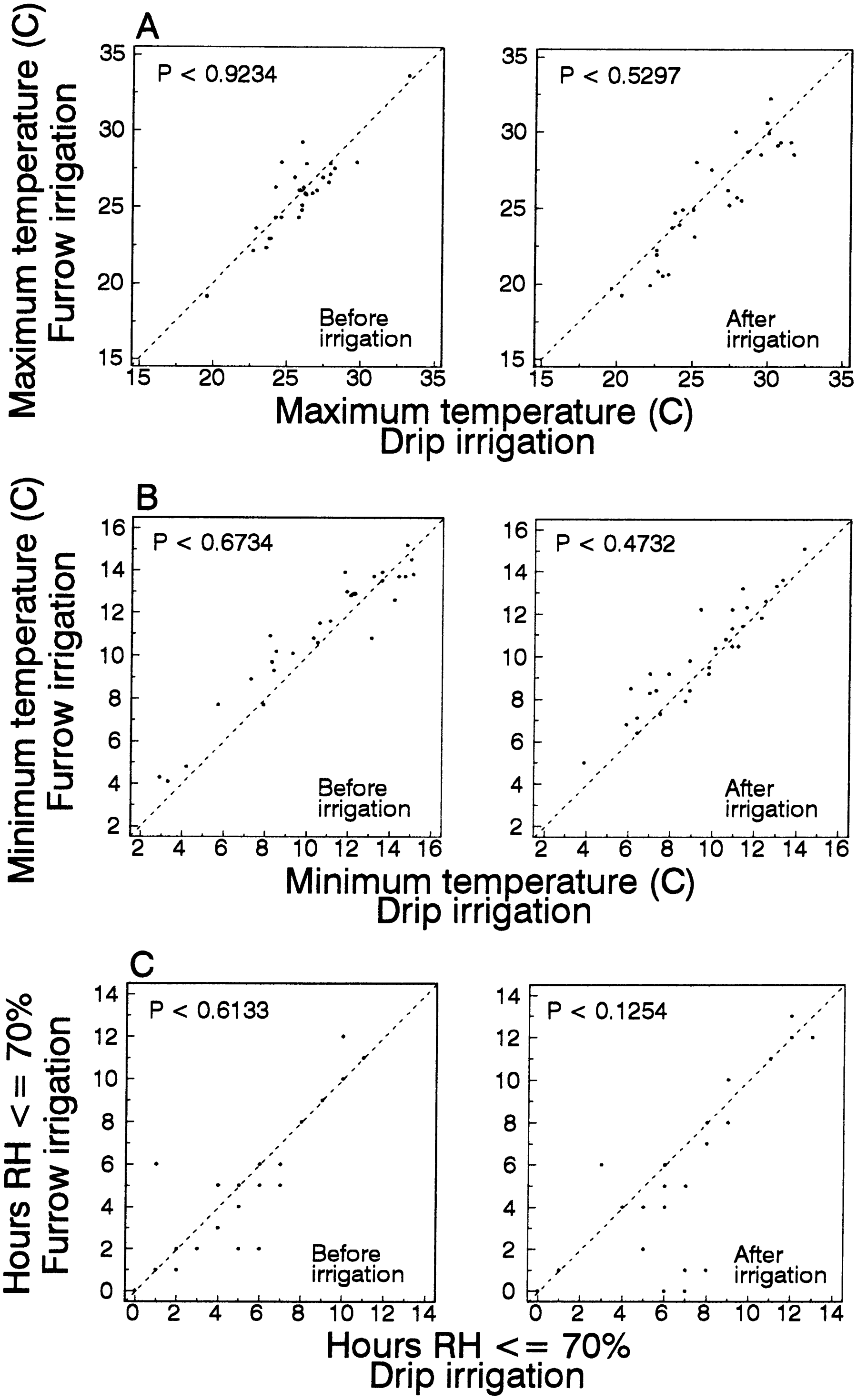

Fig. 3. Daily values of **(A)** maximum air temperature, **(B)** minimum air temperature, and **(C)** hours with relative humidity (RH) ≤ 70% in paired lettuce fields with subsurface drip and furrow irrigation before or after irrigation events. The dotted lines show a 1:1 relationship. *P*-values are for the null hypothesis that differences between the two irrigation methods have a median of zero (Wilcoxon's Signed Rank Test). Each figure contains data from 30 days, but some data points are overlapping.

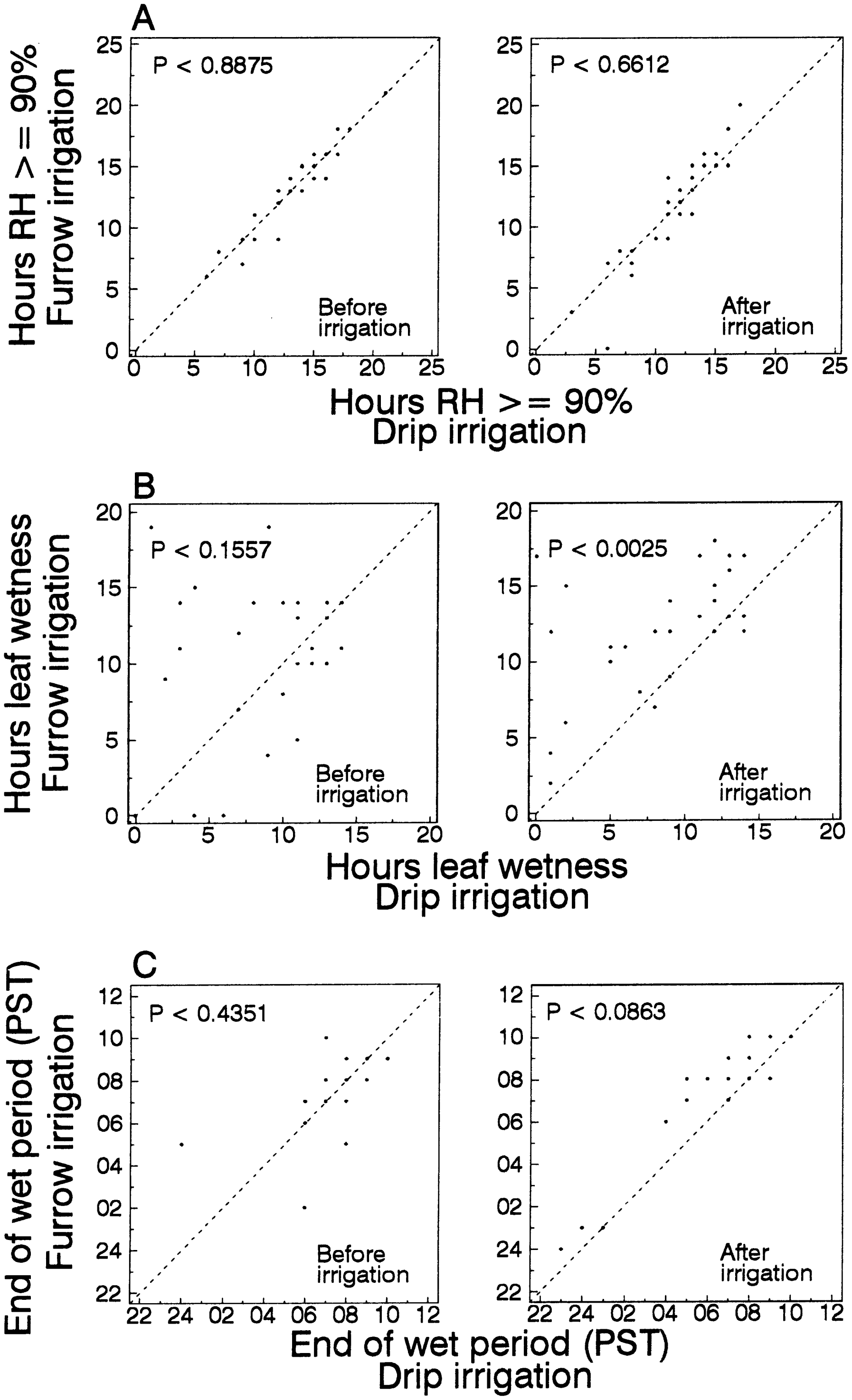

Fig. 4. Daily values of **(A)** hours with relative humidity (RH) ≥ 90%, **(B)** leaf wetness duration, and **(C)** end of morning wet period in paired lettuce fields with subsurface drip and furrow irrigation before or after irrigation events. The dotted lines show a 1:1 relationship. *P*-values are for the null hypothesis that differences between the two irrigation methods have a median of zero (Wilcoxon's Signed Rank Test). Each figure contains data from 30 days, but some data points are overlapping. PST = Pacific Standard Time.

and evaporation in the morning may be stronger.

Although microclimate differences between drip- and furrow-irrigated fields were statistically significant when the ten irrigation events were pooled and then analyzed, it should be noted that such differences were not apparent for all irrigation events. The differences were clearly influenced by the synoptic weather pattern. They were larger during warm and dry periods than during cool and moist periods (compare Figures 1 and 2).

Regarding the biology and epidemiology of downy mildews, lower values of daytime humidity and shorter leaf wetness periods in drip-irrigated fields could reduce spore survival (3,21) and infection (15,22,24,26,29), respectively. However, only in trial 5 did we find differences in disease intensity between the two irrigation methods that could be considered biologically important. During the four irrigation events (24 days) that occurred during this trial, leaf wetness ended at 1000 h in the morning or later on 6 days in the furrow-irrigated field, but only on 2 days in the field with drip irrigation. This observation is consistent with our earlier finding that wetness periods persisting until 1000 h or later are needed for infection of lettuce by downy mildew in California (24). Spore dispersal and infection can occur concurrently during such periods (25), leading to favorable conditions for infection. In trials 2, 3, and 4, during which very low levels of disease occurred, leaf wetness never ended later than 0900 h.

In all trials in which downy mildew did develop (four of the five trials), disease intensity was lower in the field with drip irrigation than in the field with furrow irrigation. However, according to the growers who cooperated with us during these trials, the magnitude of the differences in disease was too small to be economically important. It appears that, on most days in coastal California, mesoclimatic variations outweigh microclimatic modifications that could potentially influence disease development. Biologically important effects are likely limited to conditions that are just marginal for establishment of downy mildew, e.g., when morning wet periods are extended from 0900 to 1000 h or later following furrow irrigation (see discussion of trial 5 above).

Regarding prediction and management of lettuce downy mildew, we conclude that distillation of moisture from wet soils does give rise to longer wet periods and therefore should be considered in a model for leaf wetness on lettuce (23). However, it may be difficult to incorporate recommendations about method and timing of irrigation into an Integrated Pest Management scheme for lettuce, because the decision to change irrigation practices is primarily motivated by horticultural, technological, and economical factors. Many growers in the coastal vegetable production areas consider implementing subsurface drip irrigation in at least some of their fields to comply with more stringent allocation of irrigation water by state and county water resources agencies. Reduced downy mildew intensity under drip irrigation, although a relatively small effect, could give growers an additional incentive for this transition.

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Table 3. Lettuce downy mildew development in paired fields with subsurface drip and furrow irrigation

Trial[a]	Irrigation method	Final disease incidence (proportions)	AUDPC (proportion days)[b]
1	Drip	1.0 ± 0	34.75 ± 1.086
	Furrow	1.0 ± 0	37.01 ± 2.093
2	Drip	0	0
	Furrow	0.013 ± 0.0250	0.09 ± 0.035
3	Drip	0	0
	Furrow	0	0
4	Drip	0.010 ± 0.0223	0.03 ± 0.004
	Furrow	0.025 ± 0.0500	0.06 ± 0.016
5	Drip	0	0
	Furrow	0.175 ± 0.1708	0.06 ± 0.016

[a] Table 1 explains the trials.

[b] Area under the disease progress curve. Values are means ± standard deviations of four subsamples within each field.

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