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In-canopy Environment of Sprinkler Irrigated Potato Fields as a Factor for Late Blight Management in the Semiarid Environment of the Columbia Basin

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Abstract Relative humidity (RH), leaf wetness and temperature were quantitatively characterized within potato crop canopies and their potential effect on late blight development was estimated in commercial potato fields under sprinkler irrigation in the Columbia Basin in 1993, 1994, 1996, 2004, and 2013. Humid periods of relative humidity > 90 % for 10 or more hours per day with mean temperatures favorable of late blight development were not observed prior to canopy closure. However, at and after canopy closure, a total of 34 of 54 (62.9 %) weeks summed over 5 fields during 1993, 1994, 1996, and 2004 had humid periods favorable for late blight development when considering 10 h humid periods, and a total of 47 of 54 (87 %) weeks had late blight favorable periods when considering 12 h humid periods. In 2013, the mean number of days per week after canopy closure from four sites ranged from 0 to 5.5 days when RH was > 90 % for at least 10 h per day, ranged from 0 to 4.3 days when RH was > 90 % for at least 12 h per day, ranged from 0 to 3.0 days when RH was > 90 % for at least 14 h per day, and ranged from 0 to 2.0 days when RH was > 90 % for at least 16 h per day. Daily hours of contiguous RH > 90 % varied between mid- and low-canopy levels, monitoring sites within fields and between fields. Daily humid periods favorable for late blight development were frequent in June at mid- and low-canopy levels and continued intermittently in July and August in 2 of 2 fields in 2013. Mean temperatures after row closure were generally favorable for late blight development during the humid periods and were > 7.2 °C in June and > 12.2 °C in July and August. Number of rainy days per week and weeks with long periods of RH > 90 % within the potato canopy was significantly correlated, indicating that rare rain events in a semi-arid environment promote long periods of RH in irrigated fields. However, favorable late blight periods occurred without rain and were a factor of sprinkler irrigation. Canopy and ambient relative humidity and temperatures were highly associated, and the association could be used to model late blight development from existing, proximal weather stations. The mean hourly RH over the trial season at all sites for potato canopies attained minima between 1500 and 1700 h in 2013 of < 46 %. From the minima the RH increased rapidly to approximately 2200 h then increased moderately until attaining maxima at 0600. Monitoring duration of RH > 90 % was more practical and efficient than monitoring leaf wetness.

Resumen Se caracterizaron cuantitativamente la humedad relativa (RH), la humedad de la hoja y la temperatura, al interior del follaje del cultivo de papa, y se estimó su efecto potencial en el desarrollo del tizón tardío en campos comerciales de papa bajo riego por aspersión en la rivera del Columbia en 1993, 1994, 1996, 2004 y 2013. No se observaron períodos de humedad relativa >90 % por 10 o más horas al día, con temperaturas medias favorables para el desarrollo del tizón tardío antes del cierre del follaje. No obstante, durante y después del cierre de la parte aérea, un total de 34 de 54 (62.9 %) semanas sumadas sobre cinco campos durante 1993, 1994, 1996 y 2004 tuvieron períodos de humedad favorables para el desarrollo del tizón cuando se consideraron lapsos de 10 horas de humedad, y un total de 47 de 54 (87 %) semanas tuvieron períodos favorables para el tizón cuando se consideraron lapsos de humedad de 12 horas. En el 2013, el promedio del número de días por semana después del cierre del follaje de cuatro sitios fluctuó de 0 a 5.5 días cuando la RH fue >90 % por lo menos 10 hs por día. La amplitud fue de 0 a 4.3

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días cuando la RH fue >90 % por lo menos 12 hs por día. El rango fue de 0 a 3.0 días cuando la RH fue >90 % por lo menos 14 hs por día, y varió de 0 a 2.0 días cuando la RH era de >90 % por lo menos 16 hs diarias. Las horas diarias de RH >90 % contiguas variaron entre niveles medio y bajo del follaje al cuantificarse sitios dentro y entre los campos. Los períodos diarios de humedad favorable para el desarrollo del tizón tardío fueron frecuentes en junio en niveles medio y bajo de follaje y continuaron intermitentemente en julio y agosto en dos de dos campos en 2013. Las temperaturas medias después del cierre del follaje fueron generalmente favorables para el desarrollo del tizón tardío durante los períodos húmedos, y fueron >7.2 ° C en junio y >12.2 ° C en julio y agosto. Como se esperaba, las temperaturas medias estuvieron negativamente correlacionadas con la humedad relativa. El número de días lluviosos por semana, y semanas con períodos largos de RH >90 % al interior del follaje de la papa, estuvieron correlacionados significativamente, indicando que eventos raros de lluvia en un ambiente semiárido promueven períodos largos de RH en campos de riego. No obstante, se presentaron períodos favorables para el tizón tardío sin lluvia, y fueron un factor en riego por aspersión. El follaje, la humedad relativa del ambiente y las temperaturas, estuvieron estrechamente asociados, y la asociación pudo usarse para modelar el desarrollo del tizón tardío de estaciones meteorológicas existentes cercanas. La media de RH por horas sobre el ciclo de cultivo de los ensayos en todos los sitios para los follajes de la papa alcanzó la mínima entre 1500 a 1700 horas en 2013 de <46 %. De la mínima, la RH se incrementó rápidamente a aproximadamente 2200 horas. Después el incremento fue moderado, hasta alcanzar una máxima a las 0600 horas de >90 %. La duración del monitoreo de RH >90 % fue más práctico y eficiente que el de la humedad de la hoja.

Keywords Microclimate · Disease forecasting · Relative humidity · Leaf wetness · Late blight management

Introduction

The Columbia Basin of Washington and Oregon is similar to other regions of the world where potato late blight, caused by *Phytophthora infestans*, is dependent on the physical environment for development (Johnson et al. 1996, 2009). Foliage and tubers of potato cultivars grown in the region are susceptible to infection (Inglis et al. 1996; Porter et al. 2004) and aggressive genotypes of *P. infestans* are often present (Miller et al. 1995; Miller and Johnson 2000; Porter and Johnson 2007). When initial inoculum of *P. infestans* is present, only a favorable environment and sufficient time are needed for epidemic development (Hirst and Stedman 1960).

The role of environment on late blight epidemics is extensively documented (Bashi et al. 1982; Harrison 1992; Minogue and Fry 1981; Rotem et al. 1971). Cool, wet weather with rainfall, ambient relative humidity above 90 %, and temperatures of 7 to 24 °C favor development of late blight (Lacey 1967; Rotem et al. 1971). Sprinkler irrigation increases late blight in semiarid regions (Easton 1982; Rotem et al. 1970; Rotem and Cohen 1974). High humidity in the crop canopy favors sporulation of *P. infestans* and leaf wetness is crucial for infection.

Early season rain is an effective predictor of potato late blight epidemics in the Columbia Basin (Johnson et al. 1998, 2009), and is likely important for the build-up of inoculum in fields during the early stage of epidemics. Early in epidemics, moisture promotes transmission of *P. infestans* from infected seed tubers to emerged shoots in fields. Transmission from seed tubers to shoots bearing sporangia can occur within 24 h during rainy weather (Johnson 2010). Secondary infections will proceed almost immediately if a favorable environment with moisture continues. Moisture is also essential for effective dissemination of sporangia to additional fields. Rain, irrigation water, and dew supply high humidity for sporulation and moisture for infection.

Solar irradiance disfavors late blight development (Johnson 2009; Mizubuti et al. 2000; Porter and Johnson 2004; Sunseri et al. 2002). Reduced solar irradiance due to cloud cover is correlated with the increasing incidence of late blight epidemics in the Columbia Basin (Johnson et al. 2009). Ultraviolet light reduces survivability of sporangia and cloudy days contribute to late blight development within fields and possible dissemination to adjacent fields (Sunseri et al. 2002).

Ambient temperatures are generally favorable for late blight development after canopy closure between crop rows in the Columbia Basin. Canopy closure is when foliage between rows come in contact and, for the main cultivars grown including Russet Burbank, generally begins from the first to second week of June in the southern Columbia Basin to the end of June in the northern Basin. The canopy environment after canopy closure often contributes to increased risk of epidemic development (Hirst and Stedman 1960; Van der Plank 1963). Dramatic shifts from local to general epidemics have been observed after canopy closure (Hirst and Stedman 1960; Johnson et al. 2003).

The Columbia Basin of south-central Washington and north-central Oregon is a major potato-growing region in North America with a semiarid environment. Over 65, 000 ha of potato are grown annually in the region with mean tuber yields exceeding 74 t/ha (Anonymous 2014). Potato is planted mainly in March through April and harvested from August through October. Most potato fields are irrigated by sprinkler, center-pivot systems.

Late blight is managed regionally in the Columbia Basin because sporangia of *P. infestans* can become airborne in turbulent air currents and be quickly and widely disseminated within the region during cloudy and wet weather (Aylor et al. 2001; Sunseri et al. 2002) and, when disease-favoring mild temperatures and rain occur, they usually prevail over the entire region (Johnson et al. 1998, 2015). Additionally, sprinkler irrigation may potentially create a favorable microclimate within the potato canopy after canopy closure. Consequently, late blight can quickly increase in a field and spread to neighboring fields and then to more distant fields (Bashi et al. 1982; Johnson et al. 2003). Late blight and other rapidly spreading foliar diseases have been managed regionally (Coakley et al. 1984; Henderson et al. 2007; Johnson et al. 1994).

Late blight has not been observed before canopy closure in the region (Johnson et al. 2009). However, once row closure has occurred, microclimate conditions generally are favorable for late blight development whenever a field is irrigated (Easton 1982). Late blight is extremely difficult to manage once the disease is established in an irrigated field. For example, in a field with inoculum originating from infected seed tubers, incidence of late blight increased from 0.2 to 70 % over a 4-week period after canopy closure even with nine applications of efficacious fungicides (Johnson et al. 2003).

The effect of microenvironment within potato canopies on late blight develop in the Columbia Basin is not fully understood and needs to be better characterized to more efficiently manage the disease. Quantitative information for temperature, relative humidity and moisture within potato canopies is needed to augment decision support and disease forecasting systems. The purpose of this study was to quantitatively characterize relative humidity, leaf wetness, and temperature, and estimate their potential effect on late blight development in commercial potato field under sprinkler irrigation in the Columbia Basin.

Materials and Methods

Air temperature, relative humidity, and leaf wetness were monitored in seven potato fields of cultivar Russet Burbank in southcentral Washington in 1993, 1994, 1996, 2004, and 2013. All fields were irrigated with overhead pivot systems. Six fields were for commercial production and one of two fields in 2013 was at the Washington State University Experiment Station at Othello, WA. Potato growth at the Experiment Station was managed using cultural practices typical for commercial potato operations in the Columbia Basin. Commercial fields were located north of Pasco in 1993 (Pasco/93), north of Pasco in 1994 (Glade/94), west of Mesa in 1996 (Mesa/96), northeast of Pasco in 1996 (Pasco/96), west of Warden in 2004 (Ward/04), and south of Eureka in 2013 (Eureka).

Soil type was a Quincy loamy fine sand at Pasco/93, Glade/94, Mesa/96, and Eureka in 2013; a Kahlotus very fine sand at Pasco/96; a Quincy fine sand at Ward/04; and a Shano silt loam at Othello in 2013. Potatoes were planted in April each year at 25.4 cm mean spacing between plants within rows and 86.4 cm distance between rows. Row furrows were approximately 15 cm below the top of formed hills.

Instrumentation

Temperature and relative humidity (RH) were recorded with hygrothermographs and leaf wetness was recorded with Datapod digital recorders (Omnidata International Inc. Logan, UT) in 1993. Temperature, RH, and leaf wetness were recorded with Datapod digital recorders in 1994 and 1996 and with Spectrum Watchdog® data loggers (Spectrum Technologies, Inc. Plainfield, IL 60585) in 2004 and 2013. Watchdog sensors for RH and temperature were model 450 or model 150 data loggers and connected to leaf wetness sensors model 3666. All sensors were calibrated together using humidity chambers and bulb thermometers, respective differences for humidity were within <2 % and temperature was <1 %. Mean hourly values were recorded and used to calculate means for each variable for various time intervals.

Hygrothermographs, digital recorder, temperature sensors, and relative humidity sensors were placed in louvered weather shelters placed approximately 15 cm above the soil surface within a plant row a third of the distance from the outer edge to the center of circular fields in 1993, 1994, 1996, and 2004. Leaf wetness sensors were 6 x 8 cm rectangular grids painted with white latex paint with approximately 10 ml lamp black added / l of paint (Sutton et al. 1984) in 1993 through 1996, and Spectrum® leaf wetness sensors were used in 2004 and 2013. Leaf wetness sensors were placed at a 45° angle to the upright main stem on the north side of plant at mid height. All sensors were calibrated prior to use and checked periodically during the assessment period.

Monitoring Sites and Timing

Watch Dog® sensors were placed within the crop canopy at two monitoring sites per field at Eureka and Othello, WA in 2013. The sites were distinguished as W and X at Eureka and Y and Z at Othello. Sites were separated by 50 m at Othello and 200 m at Eureka and contained sensors with rain and solar shields supported with PVC pipe place in a row furrow. Sensors at each site recorded mean hourly data for temperature and RH at two canopy levels. One canopy level (low-canopy) was at 12 to 15 cm above top of potato hill (base of stem crown) and the second level (mid-canopy) was 30 to 33 cm above the top of the hill. Leaf wetness sensors were placed even with the top of the hill within the furrow at one site

(site Z Othello) and at the mid-canopy level at both sites at Othello and Eureka.

Ambient environment data for temperature and rainfall were taken from Washington State University AGWeatherNet (AWN) stations nearest the trial field stations. In 2013 the Othello AWN was 100 m from the Othello canopy sites and the Fishhook AWN was 1200 m from the Eureka sites.

For the fields studied in 1993 through 2004, the monitoring of environmental variables started approximately 60 days after planting and was at or before canopy closure in late May (1 to 2 weeks prior to row closure) to early June and continued until mid- to late August. In 2013, environmental variables were recorded approximately 60 days after planting in fields near row closure on 1 June at Eureka and 15 June at Othello. Data were collected through 30 August which was toward the end of tuber bulking and the start of canopy collapse and before exposure of sensors to direct sun light, giving 77 and 91 days of data at Othello and Eureka, respectively.

Irrigation

All irrigations were monitored, recorded, and scheduled using soil moisture data from neutron probes at both fields in 2013 by the same consultant (Professional AG Services, Pasco WA 99301). Irrigation amounts were collected twice weekly at 3 and 4 day intervals throughout the season. Irrigation start and end times varied daily over the season for both fields in 2013 where amount and hours of irrigation was dependent on depths of soil moisture capacity. Because of this variation and being no consistent sign for an irrigation event over the sensor sites, irrigation was treated as random for each hour of data collected.

Data Management and Late Blight Favorable Conditions

Hours of RH > than 10, 12, 14, and 16 h/day were calculated for 24 h periods beginning at noon each day of the monitoring period of each year. This permitted the recording of humid and wet periods as occurring on a single day, inasmuch as these variables regularly increased in the evening and continued into the next morning (Thurston et al. 1958). Individual days were grouped into 7 day weekly periods through the trial period for summary statistics. Mean temperature was calculated for periods when RH was > 90 %.

Due to a large variation between years, cultivation, and weather, data for the five fields taken from 1993 through 2004 were presented separately. Data in 2013 for the four sites from two fields were combined and also reported separately. The 2013 data added descriptive statistics between in-field sites, between fields, and proximal ambient sites to further characterize daily and seasonal environment variation within the canopy.

Favorable periods for late blight development were similar to those suggested by Wallin (Wallin 1962; Wallin and Waggoner 1950) and used by Thurston et al. (1958) wherein: RH > 90 % and mean temperatures for a 10 h period were 15.5 to 25 °C, for 12 h 12.2 to 25 °C, and for 14 and 16 h were 7.2 to 25 °C. These conditions were considered favorable only if the maximum temperature during the following 24 h did not exceed 35 °C (Thurston et al. 1958).

Data Analysis

Mean daily data were taken through the season for the variables RH, leaf wetness, temperature, days that had periods of contiguous hours of RH > 90 %, duration of leaf wetness, and mean temperatures coinciding with hourly periods of RH > 90 %. To facilitate tracking these variables throughout the season, daily data were reported in descriptive formats as mean days per week that met RH and temperature criteria for five single fields over various years between 1993 and 2004 (Table 1), combined sites within fields in 2013 (Table 2) and statistical comparisons between sites in 2013 (Table 3).

The 2013 sites contained a detailed data set for periods of RH and temperatures that were aligned in time that utilized matching irrigation management methods for the fields. Consequently the 2013 data was used to statistically compare factors within and between sites. Since row closure was offset 14 days between fields in 2013, data for sites and levels of canopy within sites were analyzed on a per field basis using PROC GLM and PROC CORR in SAS statistical software ver. 9.2 (SAS Institute Inc., Cary NC, USA). Site comparisons within fields used the mean weekly data as repeated measures on canopy levels for variables and were analyzed by hypothesis tests in a one-way repeated measures analysis of variance in Proc GLM. Sites were treated as random and canopy levels were fixed. Significant differences for variables among canopy levels for each field were then derived by Least Square Means tests using week x site as the error term. Weekly data for fields was $n = 13$ weeks (91 days) at Eureka and $n = 11$ weeks (77 days) at Othello. Results were assigned $P = 0.05$ significance level and reported as total number days out of trial days for each field for the listed variables.

Descriptive statistics for the 2013 data were generated for the mean and standard error of hourly RH and temperature ($n = 24$ h) over the trial from canopy closure to 30 August for the mid-canopy level for sites at Eureka ($n = 91$ days) and Othello ($n = 77$ days), and for corresponding ambient RH and temperature (Table 4).

Pearson correlation coefficients for data collected in 2013 were used to assess the linear relationship between the mean

Table 1 Number of days per week with 10, 12, 14, and 16 contiguous hours of relative humidity > 90 % and corresponding mean temperatures within plant canopies of potato cultivar Russet Burbank in five commercial potato fields over the growing season in southcentral Washington state in 1993, 1994, 1996, and 2004

Week[b]	Pasco/93[a]		Glade/94[a]		Mesa/96[a]		Pasco/96[a]		Ward/04[a]	
	RH > 90 d/wk[c]	C°[d]	RH > 90 d/wk[c]	C°[d]	RH > 90 d/wk[c]	C°[d]	RH > 90 d/wk[c]	C°[d]	RH > 90 d/wk[c]	C°[d]
10 h										
5/25–5/31	–[e]	–	2	10	–	–	2	12	–	–
6/1–6/7	5 [f]	16	4 [f]	12	2 [f]	18	1 [f]	15	–	–
6/8–6/14	6	14	3	12	3	16	1	16	–	–
6/15–6/21	6	17	2	17	5	14	5	15	–[f]	–
6/22–6/28	3	14	2	22	7	16	6	17	6	16
6/29–7/5	4	14	3	14	6	20	1	19	5	15
7/6–7/12	7	14	2	14	6	21	5	21	2	12
7/13–7/19	7	15	6	16	5	16	4	17	4	13
7/20–7/26	5	15	3	17	5	22	7	23	6	16
7/27–8/2	5	14	3	16	3	19	5	16	4	15
8/3–8/9	2	17	4	13	5	20	3	20	4	15
8/10–8/16	3	14	4	14	4	19	5	17	7	14
8/17–8/23	–	–	–	–	–	–	3	19	2	17
12 h										
5/25–5/31	–[e]	–	0	–	–	–	0	–	–	–
6/1–6/7	5 [f]	16	3 [f]	12	0 [f]	–	0 [f]	–	–	–
6/8–6/14	5	15	2	14	3	16	0	–	–	–
6/15–6/21	6	17	2	17	5	14	4	15	–[f]	–
6/22–6/28	3	14	1	11	6	16	5	17	5	16
6/29–7/5	3	15	2	15	4	19	1	21	5	15
7/6–7/12	6	13	0	–	4	21	4	21	1	14
7/13–7/19	7	15	6	16	4	17	4	17	3	14
7/20–7/26	3	15	1	15	5	22	5	22	4	17
7/27–8/2	4	14	2	16	1	19	3	17	0	–
8/3–8/9	2	17	2	14	3	21	1	23	2	15
8/10–8/16	2	15	4	14	3	18	3	17	2	14
8/17–8/23	–	–	–	–	–	–	3	19	2	17
14 h										
5/25–5/31	–[e]	–	0	–	–	–	0	–	–	–
6/1–6/7	5 [f]	16	2 [f]	12	0 [f]	–	0 [f]	–	–	–
6/8–6/14	5	15	2	14	0	–	0	–	–	–
6/15–6/21	5	22	2	17	3	15	2	14	–[f]	–
6/22–6/28	1	12	0	–	5	17	1	18	3	17
6/29–7/5	2	15	2	14	3	19	0	–	0	–
7/6–7/12	2	25	0	–	2	22	2	20	0	–
7/13–7/19	5	15	1	16	4	17	2	16	0	–
7/20–7/26	1	16	0	–	4	22	5	22	2	20
7/27–8/2	0	–	1	16	0	–	1	19	0	–
8/3–8/9	0	–	0	–	0	–	0	–	1	17
8/10–8/16	1	16	0	–	0	–	0	–	1	15
8/17–8/23	–	–	–	–	–	–	2	19	0	–
16 h										
5/25–5/31	–[e]	–	0	–	–	–	0	–	–	–
6/1–6/7	3 [f]	16	0 [f]	–	0 [f]	–	0 [f]	–	–	–

Table 1 (continued)

Week[b]	Pasco/93[a]		Glade/94[a]		Mesa/96[a]		Pasco/96[a]		Ward/04[a]	
	RH > 90 d/wk[c]	C°[d]	RH > 90 d/wk[c]	C°[d]	RH > 90 d/wk[c]	C°[d]	RH > 90 d/wk[c]	C°[d]	RH > 90 d/wk[c]	C°[d]
6/8–6/14	4	15	0	–	0	–	0	–	–	–
6/15–6/21	4	19	1	15	2	16	1	14	–[f]	–
6/22–6/28	1	12	0	–	2	18	1	18	0	–
6/29–7/5	1	14	0	–	0	–	0	–	0	–
7/6–7/12	0	–	2	15	1	23	2	20	0	–
7/13–7/19	4	15	0	–	2	17	1	15	0	–
7/20–7/26	0	–	0	–	2	22	1	21	1	21
7/27–8/2	0	–	0	–	0	–	0	–	0	–
8/3–8/9	0	–	0	–	0	–	0	–	0	–
8/10–8/16	1	16	0	–	0	–	0	–	0	–
8/17–8/23	–	–	–	–	–	–	1	18	0	–

[a] Fields were in southcentral Washington State north of Pasco in 1993 and 1994, west of Mesa in 1996, northeast of Pasco in 1996, and west of Warden in 2004 and were designated as Pasco/93, Glade/94, Mesa/96, Pasco/96, and Ward/04, respectively

[b] Seven day periods of data collection where field data was recorded within 2 days of start time of initial period

[c] Mean days per 7 day period that had a minimum of 10, 12, 14, or 16 h > 90 % RH

[d] Mean canopy temperature (C°) per 7 day period that corresponded to data associated within each 10, 12, 14, or 16 h interval > 90 % RH

[e] (−) = sensors either not in place or zero wet period and calculation for temperature was not relevant

[f] Period of canopy closure for fields

hourly data over the trial period at each monitoring site among the variables of RH, temperature, and leaf wetness within mid-canopy. Similarly correlation coefficients were made to assess the linear relationship between mid-canopy measurements with proximal ambient measurements (Table 5). Pearson correlations for the two fields in 2013 were used to determine if the number of days per week having 10, 12, 14, and 16 continuous hours of RH > 90 % at mid-canopy was correlated to the number of days per week having an ambient rain event or total ambient rain over the trial period (Table 6).

Results

1993 to 2004 Canopy

Prior to canopy closure, 2 days per week were observed when RH was > 90 % for at least10 h per day at Glade/94 and Pasco/96. Mean temperatures during the humid periods were < 15.5 °C; therefore, the humid periods were considered not to be favorable for late blight development. There were no days before row closure when RH was > 90 % for 12 h (Table 1). Sensors were not placed in the other three fields before row closure from 1993 to 2004.

At and after canopy closure, number of days per week when RH was > 90 % for at least 10 h in 1993, 1994, 1996, and 2004 ranged from 1 to 7. Mean temperatures during humid periods were > 15.5 °C for 5 of 11 weeks at each Pasco/93 and Glade/94, 10 of 11 at Mesa/96, 10 of 12 at Pasco/96, and 3 of 9 at Ward/04 (Table 1). A total of 33 of 54 (61.1 %) weeks summed over the 5 fields had humid periods favorable for late blight development when considering 10 h periods.

Number of days per week at and after canopy closure when RH was > 90 % for 12 h per day and mean temperature > 12 °C ranged from 2 to 7 days for 11 of 11 weeks at Pasco/93, 1 to 6 days for 8 of 11 at Glade/94, 1 to 6 days for 10 of 11 at Mesa/96, 1 to 5 days for 10 of 12 at Pasco/96, and 1 to 5 days for 8 of 9 at Ward/04 (Table 1). A total of 47 of 54 (87 %) weeks were considered favorable for late blight when summed over the 5 fields with 12 h humid periods with mean temperatures > 12 °C.

Relative humidity was > 90 % and mean temperature was > 7.2 °C after canopy closure for 14 h per day for ≥ 1 day a week for 9 of 11 weeks at Pasco/93, 6 of 11 at Glade/94 and at Mesa/96, 7 of 12 at Pasco/96, and 4 of 9 at Ward/04. Mean temperature during all these humid periods was > 7.2 °C, indicating favorable late blight. Consequently, a total of 32 of 54 (59.3 %) weeks were considered favorable for late blight when summed over the 5 fields with 14 h humid periods.

Relative humidity was > 90 % after canopy closure for 16 h per day for ≥ 1 days a week for 7 of 11 weeks at Pasco/93, 2 of 11 weeks at Glade/94, 5 of 11 weeks at Mesa/96, 6 of 12 weeks at Pasco/96, and 1 of 9 weeks at Ward/04 (Table 1). Mean temperature during all these humid periods as > 7.2 °C, indicating favorable late blight. A total of 21 of 54 weeks summed

Table 2 Mean number of days per week with 10, 12, 14, and 16 continuous hours of relative humidity > 90 % and corresponding mean temperatures within plant canopies of potato cultivar Russet Burbank at two sites in each of two fields over the growing season in southcentral Washington in 2013

Week[a]	Total Sites[b]	Days rain	Hours of contiguous canopy relative humidity > 90 % and temperature											
			10 h/day			12 h/day			14 h/day			16 h/day		
			RH ± se[c] d /week	C° ± se[d]	Sites n[e]	RH ± se[c] d /week	C° ± se[d] .	Sites n[e]	RH ± se[c] d /week	C° ± se[d]	Sites n[e]	RH ± se[c] d /week	C° ± se[d]	Sites n[e]
6/1–6/7	2 [f]	0	4.5 ± 1.50	11.5 ± 0.11	2	0	.	0	0	.	0	0	.	0
6/8–6/14	2	0	4.0 ± 1.00	9.3 ± 0.02	2	2.0 ± 0.00	9.6 ± 0.00	1	0	.	0	0	.	0
6/15–6/21	4 [g]	4.0	4.5 ± 0.29	9.7 ± 0.30	4	3.3 ± 0.50	11.9 ± 0.00	4	3.0 ± 0.00	14.2 ± 0.44	4	2.0 ± 0.41	13.1 ± 0.25	4
6/22–6/28	4	3.5	5.5 ± 0.29	16.5 ± 0.93	4	4.3 ± 0.96	14.5 ± 0.61	4	2.0 ± 0.41	14.7 ± 0.91	4	1.3 ± 0.33	13.9 ± 0.84	3
6/29–7/5	4	0.5	1.8 ± 1.50	15.8 ± 0.00	4	1.0 ± 0.00	18.8 ± 0.52	3	0	.	0	0	.	0
7/6–7/12	4	0.0	2.0 ± 0.00	13.3 ± 0.66	3	1.0 ± 0.00	14.7 ± 0.00	1	0	.	0	0	.	0
7/13–7/19	4	0.0	2.0 ± 0.00	13.1 ± 0.86	3	1.0 ± 0.00	14.6 ± 0.00	1	0	.	0	0	.	0
7/20–7/26	4	0.0	4.0 ± 0.00	13.9 ± 0.00	1	1.0 ± 0.00	14.7 ± 0.00	1	0	.	0	0	.	0
7/27–8/2	4	1.0	3.8 ± 1.28	13.4 ± 0.18	4	1.8 ± 0.96	15.6 ± 0.42	4	1.0 ± 0.00	15.9 ± 0.10	2	1.0 ± 0.00	15.9 ± 0.09	2
8/3–8/9	4	1.0	2.3 ± 0.33	15.2 ± 0.74	3	1.0 ± 0.00	15.4 ± 0.02	2	.	.	0	0	.	0
8/10–8/16	4	0.5	1.5 ± 0.50	16.8 ± 0.07	2	1.0 ± 0.00	.	1	1.0 ± 0.00	15.3 ± 0.00	1	0	.	0
8/17–8/23	4	0.0	0	.	0	.	.	0	.	.	0	.	.	0
8/24–8/30	4	1.0	1.3 ± 0.50	12.9 ± 0	4	1.0 ± 0.00	14.6 ± 0.35	4	0	.	0	0	.	0

[a] Seven day periods where means of station data was collected over season

[b] Number of sites where data was collected during each 7 day range

[c] Mean days per 7 day period with standard error among sites that had a minimum of 10, 12, 14, or 16 h > 90 % RH

[d] Mean canopy temperature (C°) per 7 day period with standard error that corresponded to sites associated within each 10, 12, 14, or 16 h interval > 90 % RH

[e] Number of sites (n) within each 7 day period that satisfied minimum interval hours > 90 % RH and used for means and standard error

[f] Canopy row closure within first field for two stations

[g] Two sites added when the second field approached canopy closure

Table 3 Number of days when relative humidity was > 90 % for 10, 12, 14, and 16 h, mean relative humidity, mean temperature, and mean temperature when relative humidity was > 90 % during the trial period at two canopy levels at two sites, within two potato circles with ambient temperature in 2013

Field (days)[a]	Canopy		Number of days for RH ≥ 90 %				mn Season	Temperature C°	
	Site	Level[b]	>10 h.	>12 h.	>14 h.	>16 h.	mn % RH	Mean	RH > 90 %
Eureka (91)	X	Upper	40 a	14 b	6 b	4	71.2 a	20.5 b	13.0 b
	X	Lower	39 a	27 a	12 a	6	76.0 a	19.8 c	14.0 a
	W	Upper	20 b	11 b	5 b	2	64.2 b	21.1 a	12.9 b
	W	Lower	19 b	11 b	7 b	3	66.0 b	20.5 b	12.9 b
		lsd	15.6	9.0	4.3	5.3	4.95	0.51	0.86
	Ambient	0	0	0	0	53.3	22.1	15.2	
Othello (77)	Z	Upper	26 b	13 b	6 b	4	69.8 b	20.7 a	13.7 b
	Z	Lower	.	.	.	.	.	.	.
	Y	Upper	24 b	14 b	6 b	4	71.2 b	20.5 b	13.9 b
	Y	Lower	37 a	28 a	13 a	8	76.9 a	19.9 c	14.8 a
		lsd	4.6	7.2	6.7	5.5	1.84	0.23	0.43
	Ambient	6	3	2	1	60.0	21.6	14.9	

[a] Number of days from canopy closer at Eureka and Othello to end of rapid tuber bulking on 30 August 2013

[b] Significance for canopy levels among variables for the two fields based on repeated measures analyses derived from thirteen and eleven weekly means for Eureka and Othello respective over a growing a season

over the 5 fields had 16 h humid periods considered favorable for late blight.

2013 Canopy Data

Data were not recorded before canopy closure on 1 June at Eureka and 15 June at Othello in 2013. Mean number of days per week with RH > 90 % ranged from 0 to 5.5 days for at least10 h per day, 0 to 4.3 days for 12 h per day, 0 to 3 days for 14 h per day, and 0 to 2 days for 16 h per day in 2013 (Table 2). Relative humidity was > 90 % for 16 h more than one day a week at 4 of 4 sites and 3 of 3 sites during the weeks of June 15 and June 22, respectively. Mean temperatures were > 15.5 °C 3 of the 12 weeks when RH was > 90 % for at least 10 h/ day, was > 12.2 °C 8 of the 11 weeks when RH was > 90 % for at least 12 h per day, and was > 7.2 °C 4 of 4 weeks for 14 h and 3 of 3 for 16 h when RH > 90 % for each 14 and 16 h, respectively, per day in 2013 (Table 2). Fourteen of the 26 humid periods after row closure were considered favorable for late blight development.

Daily hours of contiguous RH > 90 % over the trial period varied between canopy levels, the two monitoring sites at each field and the fields at each Eureka and Othello in 2013. Daily humid periods favorable for late blight development were frequent in June for both canopy levels at both sites in both fields (Figs. 1 and 2). Favorable humid periods in July and August were occasional at both sites at Eureka and Othello, but were present the end of July and early August at the X site at Eureka and at both sites at Othello (Figs. 1 and 2). Mean temperature were > 7.2 °C in June and > 12.2 °C in July and August (Figs. 1 and 2).

Twice the number of days with RH > 90 % for 10 h for the mid- and low-canopies was observed at site X than site W at Eureka over the trial period. The difference was statistically significant ($P < 0.05$). Similarly, the low-canopy at site X at Eureka had significantly more days with RH > 90 % for 12 and 14 h than either canopy level at site W at Eureka. Mean RH for the trial period was significantly greater at Eureka site X for the mid- and low-canopy levels than either canopy level at site W. However, at Othello, mean RH and hours of RH >90 % did not differ significantly between sites at the mid-canopy level, but RH categories differed significantly between the mid- and low-canopy levels at site Y (Table 3). Mean RH was higher and mean temperature was lower within the canopy than ambient conditions at both fields in 2013 (Tables 3 and 4).

Relative humidity and temperatures were higher at the Othello ambient station than the Eureka ambient station for similar hours and were generally reflected within the canopy for the corresponding field sites. Standard errors generally decreased as RH increased approaching saturation as did the corresponding declining temperatures (Table 4).

Curves for RH verses 24 h time periods for the two monitoring sites and ambient weather station near Eureka had similar shapes but differed in magnitude (Table 4 and Fig. 3). Data for the hourly time periods at the Othello sites, along with the ambient weather station, had similar responses and differed in

Table 4 Percent relative humidity (RH) and temperature (C°) within potato canopy taken as a mean for each daily hour over a range of days from canopy closure to 30 August for two fields each having two sites with corresponding out of field ambient data

	Field Eureka n = 91 days						Field Othello *n* = 77 days					
	Ambient		Site W		Site X		Ambient		Site Y		Site Z	
Hours	RH ± se	C° ± se	RH ± se	C° ± se	RH ± se	C° ± se	RH ± se	C° ± se	RH ± se	C° ± se	RH ± se	C° ± se
1	67 ± 1.3	17 ± 0.3	79 ± 1.6	15 ± 0.4	89 ± 1.2	14 ± 0.3	68 ± 1.7	18 ± 0.3	83 ± 1.8	15 ± 0.3	83 ± 1.7	15 ± 0.3
2	69 ± 1.2	16 ± 0.3	83 ± 1.4	14 ± 0.3	90 ± 1.1	13 ± 0.3	70 ± 1.5	16 ± 0.3	85 ± 1.5	15 ± 0.3	86 ± 1.5	14 ± 0.3
3	72 ± 1.2	15 ± 0.3	85 ± 1.3	14 ± 0.3	92 ± 1.0	13 ± 0.3	74 ± 1.5	16 ± 0.3	89 ± 1.2	14 ± 0.3	90 ± 1.1	14 ± 0.3
4	74 ± 1.2	15 ± 0.4	87 ± 1.2	13 ± 0.3	93 ± 0.9	12 ± 0.3	76 ± 1.4	16 ± 0.3	92 ± 0.8	13 ± 0.2	92 ± 0.9	13 ± 0.2
5	75 ± 1.1	15 ± 0.3	89 ± 1.1	12 ± 0.3	94 ± 0.8	12 ± 0.3	78 ± 1.3	14 ± 0.3	94 ± 0.6	13 ± 0.2	94 ± 0.6	13 ± 0.3
6	73 ± 1.1	16 ± 0.3	90 ± 1.1	12 ± 0.4	95 ± 0.7	12 ± 0.3	80 ± 1.2	14 ± 0.2	95 ± 0.6	13 ± 0.2	95 ± 0.6	13 ± 0.2
7	66 ± 1.2	18 ± 0.3	89 ± 1.1	14 ± 0.3	93 ± 1.0	16 ± 0.3	78 ± 1.2	16 ± 0.3	95 ± 0.6	14 ± 0.2	93 ± 0.8	15 ± 0.2
8	60 ± 1.2	20 ± 0.4	78 ± 1.5	18 ± 0.4	82 ± 1.7	19 ± 0.4	74 ± 1.4	18 ± 0.3	88 ± 1.3	17 ± 0.3	82 ± 1.6	19 ± 0.3
9	55 ± 1.2	22 ± 0.4	68 ± 1.7	21 ± 0.4	71 ± 1.7	22 ± 0.4	68 ± 1.5	20 ± 0.4	77 ± 1.9	20 ± 0.4	71 ± 2.0	22 ± 0.4
10	50 ± 1.2	24 ± 0.4	61 ± 1.7	23 ± 0.4	61 ± 1.8	24 ± 0.4	62 ± 1.6	22 ± 0.4	68 ± 2.0	23 ± 0.4	62 ± 2.2	24 ± 0.5
11	45 ± 1.2	25 ± 0.4	53 ± 1.7	25 ± 0.5	55 ± 1.8	26 ± 0.4	56 ± 1.7	22 ± 0.4	61 ± 2.1	25 ± 0.5	55 ± 2.3	27 ± 0.6
12	41 ± 1.2	27 ± 0.5	47 ± 1.8	27 ± 0.5	51 ± 1.8	28 ± 0.5	52 ± 1.7	24 ± 0.5	56 ± 2.1	27 ± 0.5	51 ± 2.2	28 ± 0.6
13	38 ± 1.2	28 ± 0.5	43 ± 1.8	29 ± 0.6	48 ± 1.9	29 ± 0.5	48 ± 1.7	26 ± 0.5	51 ± 2.1	28 ± 0.5	48 ± 2.1	29 ± 0.6
14	35 ± 1.3	29 ± 0.5	39 ± 1.9	30 ± 0.6	45 ± 1.8	30 ± 0.5	46 ± 1.6	26 ± 0.5	49 ± 2.0	29 ± 0.5	46 ± 2.1	30 ± 0.6
15	33 ± 1.3	29 ± 0.5	37 ± 1.9	31 ± 0.6	43 ± 1.8	30 ± 0.6	44 ± 1.7	28 ± 0.5	46 ± 2.1	29 ± 0.6	43 ± 2.0	30 ± 0.6
16	33 ± 1.2	30 ± 0.5	37 ± 1.9	30 ± 0.6	42 ± 1.8	30 ± 0.5	42 ± 1.8	28 ± 0.5	46 ± 2.0	29 ± 0.5	43 ± 2.1	30 ± 0.6
17	33 ± 1.2	30 ± 0.5	35 ± 1.7	30 ± 0.6	43 ± 1.7	29 ± 0.5	42 ± 1.7	28 ± 0.6	45 ± 2.0	28 ± 0.5	44 ± 2.1	28 ± 0.5
18	36 ± 1.4	29 ± 0.5	37 ± 1.7	29 ± 0.5	49 ± 1.8	27 ± 0.5	42 ± 1.8	28 ± 0.6	50 ± 2.1	27 ± 0.5	51 ± 2.0	26 ± 0.5
19	43 ± 1.4	27 ± 0.5	44 ± 1.8	28 ± 0.5	61 ± 1.6	25 ± 0.4	46 ± 1.9	28 ± 0.6	58 ± 1.9	25 ± 0.4	62 ± 1.8	23 ± 0.4
20	51 ± 1.4	23 ± 0.4	58 ± 1.6	24 ± 0.4	74 ± 1.2	20 ± 0.3	52 ± 1.9	26 ± 0.5	69 ± 1.7	21 ± 0.4	71 ± 1.8	20 ± 0.3
21	54 ± 1.5	21 ± 0.4	71 ± 1.4	19 ± 0.3	81 ± 1.2	17 ± 0.3	56 ± 1.9	22 ± 0.5	75 ± 1.9	18 ± 0.3	76 ± 1.9	18 ± 0.3
22	56 ± 1.5	20 ± 0.4	75 ± 1.6	17 ± 0.4	85 ± 1.4	16 ± 0.3	58 ± 1.8	22 ± 0.4	78 ± 1.8	17 ± 0.3	78 ± 2.0	17 ± 0.3
23	60 ± 1.5	19 ± 0.4	76 ± 1.8	16 ± 0.4	86 ± 1.5	15 ± 0.3	62 ± 1.8	20 ± 0.4	79 ± 1.9	16 ± 0.3	79 ± 2.0	16 ± 0.3
24	64 ± 1.4	18 ± 0.3	78 ± 1.8	16 ± 0.4	86 ± 1.4	14 ± 0.3	66 ± 1.7	18 ± 0.3	81 ± 1.9	16 ± 0.3	81 ± 1.8	15 ± 0.3

magnitude (Table 4). The mean hourly RH over the trial season at all sites for potato canopy and ambient attained minima between 1500 to 1700 h in 2013. From the minima the RH increased rapidly to approximately 2200 h then increased moderately until attaining maxima at the 0600 h for sites in both fields (Table 4).

Curves for temperature conversely mirrored the RH curves at Eureka (Fig. 3) and similarly at Othello (Table 4). Ambient RH was consistently less and ambient temperature was greater than values recorded in the potato canopy after row closure.

Mean RH and hours of RH > 90 % were higher in June than in July and August, and values at the low inflection were higher in July than August at one but not the other monitoring site at Eureka (Fig. 4). Similar observations were made at Othello, but the difference in magnitude was less which had offset and reduced data periods than the Eureka sites (Fig. 5).

Length of daily wet periods varied but were often > 15 h per day at each of two monitoring sites in each field in 2013 (Fig. 6). Lengths of leaf wetness were exceptionally long at the X site at Eureka, which was located in low area in the field. Lengths of leaf wetness were similar in fields during 1993, 1994, 1996, and 2004 (data not shown).

Correlation coefficients comparing hourly data over a season for RH and temperatures within the mid-canopy level ranged from −0.84 to −0.89 over all sites for hourly data over the trial period. Similarly, correlation coefficients ranged from 0.41 to 0.53 when RH was compared to leaf wetness and ranged from −0.19 to 0.33 when temperature was compared to leaf wetness. All Pearson correlations were significant at $P < 0.0001$ (Table 5). Correlation coefficients ranged from 0.77 to 0.85 for hourly mid-canopy RH compared to ambient RH at all sites, ranged from 0.74 to 0.96 for mid-canopy and ambient temperatures, and ranged from 0.09 to 0.24 for mid-canopy and ambient leaf wetness (Table 5).

Mean number of rainy days per week ranged from 0.3 to 1.8 during the trial periods in 1993 to 2004, and from 0 to 4.0 during the trial period in 2013 (Table 2). Natural precipitation and irrigation amounts differed for the two fields in 2013.

Table 5 Correlation coefficients for corresponding hourly data over the trial period among relative humidity (RH), temperature (C °), and leaf wetness (LW) within the potato mid-canopy level and for correlations between ambient and canopy data at two separated sites each within two fields in Washington in 2013

Pearson correlation coefficients |r|[a]				
Field / site[b]	Within canopy |r|		Ambient[c] x Canopy |r| [d]	
Eureka/W	RH x C °	−0.89	RH	0.84
	RH x LW	0.53	C °	0.96
	C ° x LW	−0.33	LW	0.24
Eureka/X	RH x C °	−0.87	RH	0.77
	RH x LW	0.41	C °	0.94
	C ° x LW	−0.19	LW	0.09
Othello/Y	RH x C °	−0.84	RH	0.76
	RH x LW	0.43	C °	0.90
	C ° x LW	−0.20	LW	0.20
Othello/Z	RH x C °	−0.86	RH	0.85
	RH x LW	0.47	C °	0.74
	C ° x LW	−0.26	LW	0.23

[a] Probability of Pearson correlations < 0.0001

[b] Correlations for each site at Eureka and Othello were $n = 2184$ and $n = 1848$ h respective

[c] Ambient weather stations were proximal to and unique to each field

[d] Leaf wetness sensors used in fields and ambient stations used linear but different scalar ordinals

Table 6 Correlation coefficients for number of days per week having 10, 12, 14, and 16 continuous hours of relative humidity (RH) > 90 % in cv Russet Burbank potato canopy relative to the number of days per week having an ambient rain event and total ambient rain per week at two fields over the trial period in Washington in 2013

Pearson correlation coefficients (r)[a]			
Field [b] (n)	Canopy RH days/week [c]	No. rainy days /wk[d] (r)	Total amount rain/wk[e] (r)
Eureka (26)			
	10 h	0.58	0.52
	12 h	0.91	0.88
	14 h	0.94	0.82
	16 h	0.90	0.81
Othello (22)			
	10 h	0.64	0.41
	12 h	0.84	0.67
	14 h	0.89	0.72
	16 h	0.77	0.56

[a] Probability of correlations $P < 0.002$ except $P = 0.05$ at Othello at 10 h RH > 90 % for amount ambient rain per week

[b] Weekly data from two sites for each field from row closer at Eureka on 6/01 and Othello on 6/15 through 8/30

[c] Data using number of days per weekly periods of RH for all hours and hours of 10, 12, 14, and 16 h of contiguous RH over 90 % at mid-canopy

[d] Data using number of days per weekly periods having measurable ambient rain events over the trial period

[e] Data using total amount of precipitation per weekly periods having measurable ambient rain events over the trial period

Eleven rainy days totaling 3.1 cm occurred during the 13 weeks of the trail period at Eureka ($n = 91$ days), and 12 rainy days totaling 5.3 cm occurred during the 11 weeks of the trial period at Othello ($n = 77$ days). Amount of irrigation water and natural rainfall per field was 55.4 cm at Eureka and 41.7 cm at Othello. The average daily irrigation and natural rain amounts over the trial periods was 0.61 cm at Eureka and 0.54 cm at Othello.

Number of rainy days per week and amount of rain per week were both significantly ($P < 0.002$) correlated with number of days per week with long periods of RH > 90 % within the potato canopy at Eureka and Othello (Table 6). For example, the correlation coefficient was 0.94 for number of rainy days per week with 14 h of RH > 90 % at Eureka, and 0.82 for total amount of rain per week with 14 h RH > 90 % at Eureka (Table 6). Correlation coefficients were higher for number of rainy days per week with hours RH > 90 % than total amount of rain per week compared to days with hours RH > 90 % at both locations. Duration of leaf wetness was not significantly correlated ($P > 0.05$) with either number of rainy days per week or amount of rain per week (data not shown).

There was a significant, positive correlation for the combined sites at Othello for biweekly (3 and 4 day) amount of irrigation water collected over the trial season compared to similar period number of days with 10, 12, 14, and 16 h RH > 90 % ($r = 0.35$ to 0.37, $P < 0.02$). However similar correlations for the individual sites were non-significant as were the combined and individual sites at Eureka. Additionally, there were no significant correlations for the weekly means for amount of irrigation water collected compared to the weekly number of days the canopy had 10, 12, 14, and 16 h RH > 90 % (data not shown). There was a negative correlation between amount of weekly irrigation water compared to amount of ambient rain ($r = -0.39$, $P = 0.07$) at Othello and similarly a stronger correlation at Eureka ($r = -0.60$, $P = 0.001$).

Discussion

The microenvironment near potato plants did not favor potential late blight development before canopy closure, and explains why late blight has not been observed in potato fields before canopy closure in the Columbia Basin. This result was expected since air movement and solar irradiance are not restricted by a dense plant canopy and ambient relative humidity is relatively low in the semiarid atmosphere. In addition,

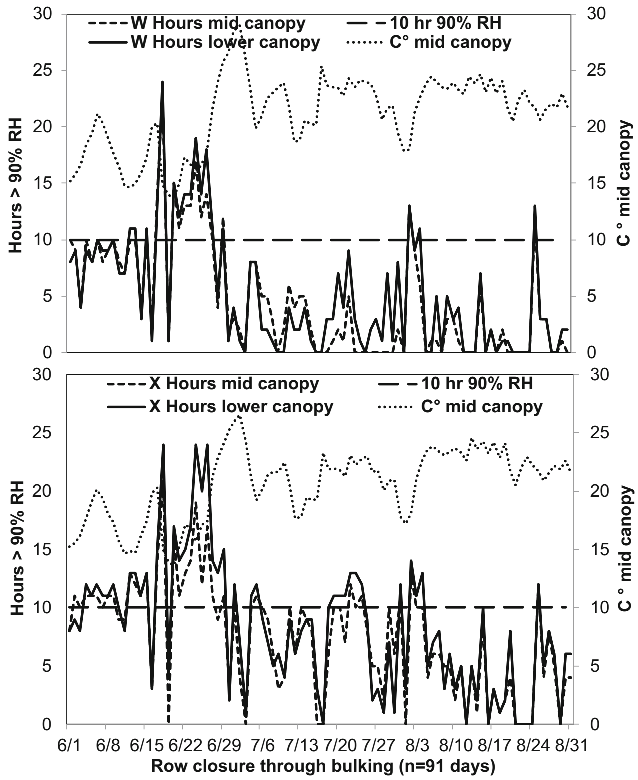

Fig. 1 Daily hours of contiguous RH > 90 % and mean temperature, when environmental conditions were favorable for late blight development according to Wallin, for the upper and lower canopies at two sites, W and X, within a sprinkler, irrigated circle of Russet Burbank potatoes near Eureka, WA in 2013

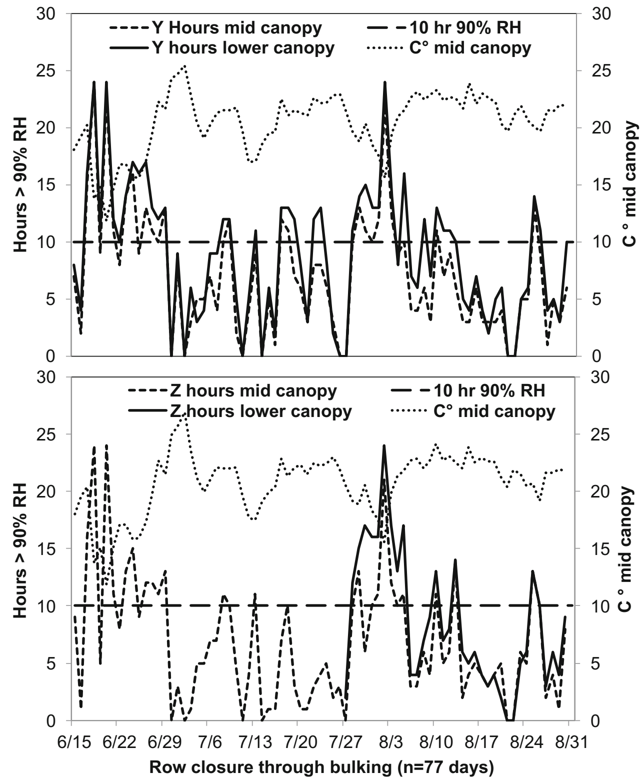

Fig. 2 Daily hours of contiguous RH > 90 % and mean temperature, when environmental conditions were favorable for late blight development according to Wallin, for the upper and lower canopies at two sites, Y and Z, within a sprinkler, irrigated circle of Russet Burbank potatoes at the Washington State University Experiment Station near Othello, WA in 2013

similar results were obtained when RH and temperature were monitored prior to row closure in commercial fields in the Columbia Basin before this study was initiated (unpublished data).

However, the microenvironment within the canopy at and after canopy closure was frequently favorable for late blight development. Potentially favorable late bight periods after canopy closure occurred up to 7 days per week and 87 % of the weeks had late blight favorable days over five fields in 1993, 1994, 1996 and 2004. Temperatures during humid periods were mostly favorable for late blight after canopy closure.

Humid periods were longer in June than in July and August. Fungicides for late blight management may be justified in June, especially after relatively wet weather in April and May, which is associated with late blight epidemics in the Columbia Basin (Johnson et al. 1996, 1998).

Favorable periods for late blight were often accompanied by rain in a study in Minnesota where potatoes were not sprinkler irrigated (Thurston et al. 1958). Rainfall, when it did occur in the semiarid environment of the Columbia Basin, was highly associated with long durations of humid periods throughout the trial period. The longest periods of RH > 90 % were highly correlated with rainy days. Rainy days are often accompanied with cloud cover and reduced solar irradiance which is associated with a high incidence of late blight in the Columbia Basin (Johnson et al. 2009). However, favorable late blight periods occurred in this study without rain and were a factor of sprinkler irrigation. Favorable periods for late blight in the Columbia Basin would be extended with rain fall

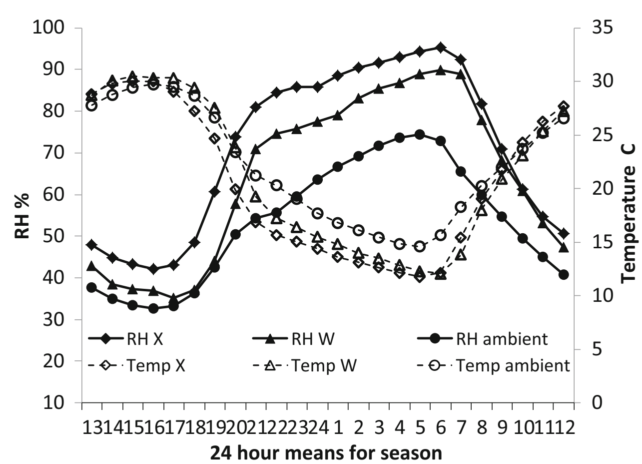

Fig. 3 Ambient and mid-canopy mean relative humidity and temperature during 24 h periods from 1 June to 30 August in a potato circle of Russet Burbank at two sites, W and X, near Eureka, WA in 2013

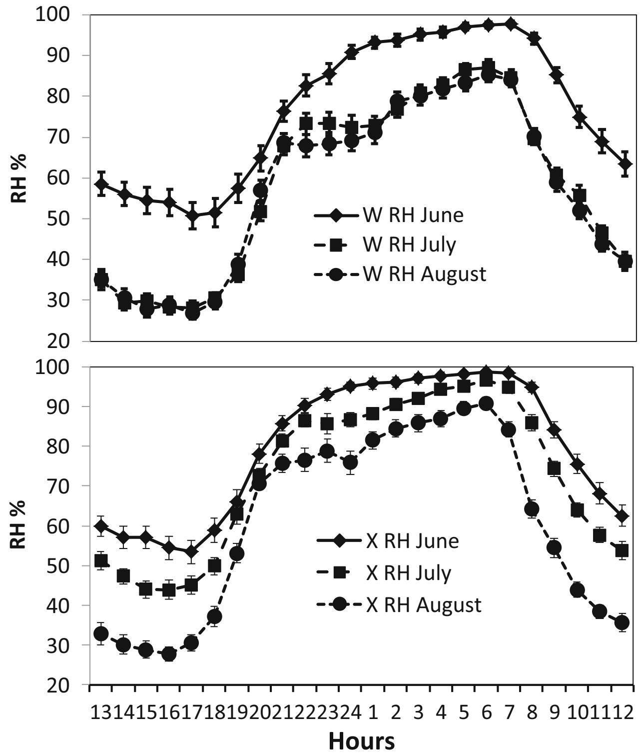

Fig. 4 Mean relative humidity during 24 h periods for early, mid, and late season growing stages within mid-canopy in a potato circle of Russet Burbank at two sites, W and X, near Eureka, WA in 2013

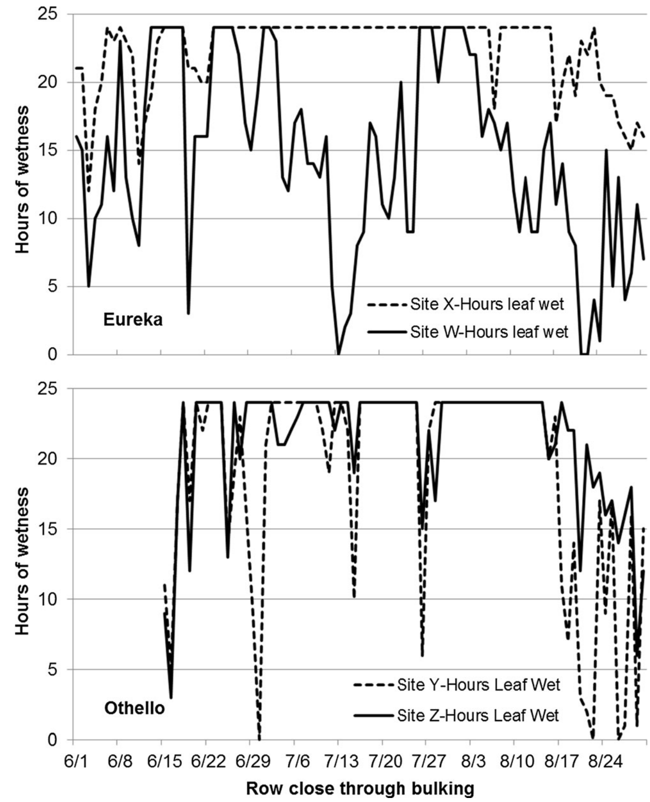

Fig. 6 Hours of leaf wetness in the plant canopy of pivot irrigation circles at two monitoring sites in commercial fields of cultivar Russet Burbank at Eureka and Othello WA in 2013

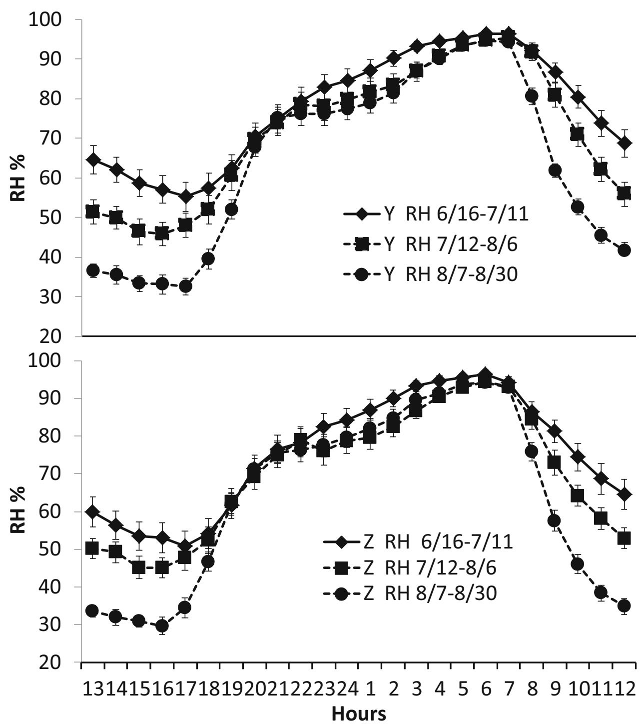

Fig. 5 Mean relative humidity during 24 h periods for early, mid, and late season growing stages within mid-canopy in a potato circle of Russet Burbank at two sites, Y and Z, near Othello, WA in 2013

and increase the potential for late blight development and promote spread within and between fields. Fungicide application just before major rainfall would be important in the Columbia Basin if inoculum is present between canopy closure and harvest (Johnson et al. 2015). Forecasts for rain are beneficial in managing late blight in the Columbia Basin (Johnson et al. 2015).

Significant differences for mean RH and number of days with hours of RH > 90 % were observed between monitoring sites at Eureka but not at Othello in 2013 (Table 3). This was largely due to differences in topography of the two fields. The field at Eureka had a gradual swale where site W was located on the crown and approximately 4 m higher than site X which was at the bottom. During field inspections the furrow adjacent to site W was dry while the furrow at site X was wet or contained water. The topography at Othello was flat with no detectable drainage differences between sites. Consequently, variation within fields needs to be considered when scouting for disease and managing late blight.

More hours of RH > 90 % occurred and mean RH was higher at the low- than the mid-canopy level at the three monitoring sites where both variables were recorded in 2013. As expected, canopy height is also a factor in placing environmental monitoring sensors and on late blight development.

Canopy temperatures were generally favorable for late blight development after canopy closure in the Columbia Basin. Low temperatures near 7 °C were sometimes encountered in June and would likely retard but may not prevent late blight development. Late blight may slowly develop in the Columbia Basin when temperatures are less than those considered as favorable in some disease forecasting models (Wallen 1962; Wallin and Waggoner 1950). Late blight development progressed slowly in the tropical highland regions of the Toluca Valley of Mexico at temperatures below thresholds of 7 to 10 °C, which were defined in north-temperate climates (Grunwald et al. 2000). Temperature thresholds established for predictive models in the north-temperate climates may not fully account for slowed progress of the pathogen at 7 to 10 °C (Grunwald et al. 2000). Relatively high levels of inoculum and long humid and wet periods may compensate for relatively low temperatures for infection (Johnson et al. 1994; Rotem et al. 1971; Rotem 1978). Because temperatures are generally favorable for late blight development, they may not need to be a major component for late blight management models after row closure for the Columbia Basin.

Hourly mid-canopy relative humidity and temperature compared to the corresponding ambient values differed in magnitude. However, the canopy and proximal ambient values were significantly and highly associated at all monitoring sites in 2013 (Table 5). This association may be used in modeling favorable conditions for late blight in a semi-arid region with existing proximal weather stations. RH varied due to canopy height and field location in this study. Such variation should be accounted for when predicting the development of late blight and in making disease management decisions.

Leaf wetness duration is difficult to define because various portions of leaves and canopies are wet and dry at different times (Huber and Gillespie 1992). Obtaining reliable data from leaf wetness sensors is problematic, especially in potato canopies, in that sensors require regularly cleaning in the field of dirt and plant material to give consistent data. Plant material such as a leaflet adhering to the sensor traps moisture between the two surfaces giving a false value, and frequent trips to clear sensors would trample surrounding foliage and thus alter the canopy microenvironment. Consequently, leaf wetness duration may be over stated in this study. However, the main point from the leaf wetness data is valid in that wet periods are sufficient in duration to promote late blight in irrigated potato fields in the Columbia Basin.

The arbitrary ordinal data among leaf wetness sensors was difficult to relate to temperatures or RH. There were low associations between hourly leaf wetness compared to temperatures and RH within the crop canopy ($r=-0.33$), and between canopy and ambient leaf wetness ($r=0.24$). Also there were no significance correlations for number of days of leaf wetness compared to days with contiguous hours of RH >90 % or days with rain for the trial season at the two fields in 2013. Leaf wetness data can be a valuable tool in environmental studies but in this study using standard RH and temperature sensing methods for canopy modeling in a semi-arid region was more practical and efficient as also noted by Rowlandson et al. (2015).

The management strategy in the Columbia Basin is to initially keep late blight out of fields. Once inoculum is in a field, the disease is extremely difficult to manage. For example, late blight incidence increased from 0.6 to 70 % in 35 days in a field of Russet Norkotah even with nine fungicide applications being made during that time period. Initial inoculum for this field originated from infected seed tubers (Johnson et al. 2003). However, fungicide applications for late blight before row closure in the Columbia Basin are likely not warranted unless a prolonged rainy period is expected. Rain forecasts are helpful in identifying future rainy periods (Johnson et al. 2015). Fungicides could then be effective in protecting foliage from infection by sporangia (Inglis et al. 1999; Powelson and Inglis 1999) that could be potentially produced on latently infected potato shoot arising from infected seed pieces (Johnson 2010; Johnson and Cummings 2013); Keary 1953), and possibly from other inoculum sources such as infected refuse tubers and infected volunteer potatoes.

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References

Anonymous. 2014. Crop Report. National Agricultural Statistics Service. U. S. Dept. Agric. Washington Field Office, Olympia, WA

Aylor, D.E., W.E. Fry, H. Mayton, and J.L. Andrade-Piedra. 2001. Quantifying the rate of release and escape of *Phytophthora infestans* sporangia from a potato canopy. *Phytopathology* 91: 1189–1196.

Bashi, E., Y. Ben-Joseph, and J. Rotem. 1982. Inoculum potential of *Phytophthora infestans* and the development of potato late blight. *Phytopathology* 72: 1043–1047.

Coakley, S.M., W.S. Boyd, and R.L. Line. 1984. Development of regional models that use meteorological variables for predicting stripe rust disease on winter wheat. *Climatic Application Meteorology* 23: 1234–1240.

Easton, G.D. 1982. Late blight of potatoes and prediction of epidemics in arid central Washington State. *Plant Disease* 66: 452–455.

Grunwald, N.J., O.A. Rubio-Covarrubias, and W.E. Fry. 2000. Potato late-blight management in the Toluca Valley: forecasts and resistant cultivars. *Plant Disease* 84: 410–416.

Harrison, J.G. 1992. Effects of the aerial environment on late blight of potato foliage – a review. *Plant Pathology* 41: 384–416.

Henderson, D., C.J. Williams, and J.S. Miller. 2007. Forecasting late blight in potato crops of southern Idaho using logistic regression analysis. *Plant Disease* 91: 951–956.

Hirst, J.M., and O.J. Stedman. 1960. The epidemiology of *Phytophthora infestans.* II. The source of inoculum. *Annual Application Biology* 48: 489–517.

Huber, L., and T.J. Gillespie. 1992. Modeling leaf wetness in relation to plant disease epidemiology. *Annual Review of Phytopathology* 30: 353–357.

Inglis, D.A., D.A. Johnson, D.E. Legard, W.E. Fry, and P.B. Hamm. 1996. Relative resistances of potato clones in response to new and old populations of *Phytophthora infestans. Plant Disease* 80: 575–578.

Inglis, D.A., M.L. Powelson, and A.E. Dorrance. 1999. Effect of registered potato seed piece fungicides on tuber-borne *Phytophthora infestans. Plant Disease* 83: 229–234.

Johnson, D.A. 2010. Transmission of *Phytophthora infestans* from infected potato seed tubers to emerged shoots. *Plant Disease* 94: 18–23.

Johnson, D.A., and R.F. Cummings. 2013. A plant stem inoculation assay for assessing transmission of *Phytophthora infestans* from potato seed tubers to emerged shoots. *Plant Disease* 97: 183–188.

Johnson, D.A., J.R. Alldredge, and J.R. Allen. 1994. Weather and downy mildew epidemics of hop in Washington State. *Phytopathology* 84: 524–527.

Johnson, D.A., J.R. Alldredge, and D.L. Vakoch. 1996. Potato late blight forecasting models for the semiarid environment of southcentral Washington. *Phytopathology* 86: 103–106.

Johnson, D.A., J.R. Alldredge, and P.B. Hamm. 1998. Expansion of potato late blight forecasting models for the Columbia Basin of Washington and Oregon. *Plant Disease* 82: 642–645.

Johnson, D.A., J.R. Alldredge, P.B. Hamm, and B.E. Frazier. 2003. Aerial photography used for spatial pattern analysis of late blight infection in irrigated potato circles. *Phytopathology* 93: 805–812.

Johnson, D.A., T.F. Cummings, R. Abi Ghanem, and J.R. Alldredge. 2009. Association of solar irradiance and days of precipitation with incidence of potato late blight in the semiarid environment of the Columbia Basin. *Plant Disease* 93: 272–280.

Johnson, D.A., T.F. Cummings, and A.D. Fox. 2015. Accuracy of rain forecasts for use in scheduling late blight management tactics in the Columbia Basin of Washington and Oregon. Plant Dis. 99:in press.

Keary, M.W. 1953. Delayed sporulation of *Phytophthora infestans* on infected potato shoots. *Plant Pathology* 2: 68–71.

Lacey, L. 1967. The role of water in the spread of *Phytophthora infestans* in the potato crop. *Annual Application Biology* 59: 245–255.

Miller, J.S., and D.A. Johnson. 2000. Competitive fitness of *Phytophthora infestans* isolates under semiarid field conditions. *Phytopathology* 90: 220–227.

Miller, J.S., D.A. Johnson, and P.B. Hamm. 1995. Aggressiveness of isolates of *Phytophthora infestans* from the Columbia Basin of Washington and Oregon. *Phytopathology* 88: 190–197.

Minogue, K.P., and W.E. Fry. 1981. Effect of temperature, relative humidity, and rehydration rate on germination of dried sporangia of *Phytophthora infestans. Phytopathology* 71: 1181–1184.

Mizubuti, E.S.G., D.E. Aylor, and W.E. Fry. 2000. Survival of *Phytophthora infestans* sporangia exposed to solar radiation. *Phytopathology* 90: 78–84.

Porter, L.D., and D.A. Johnson. 2004. Survival of *Phytophthora infestans* in surface water. *Phytopathology* 94: 380–387.

Porter, L.D., and D.A. Johnson. 2007. Survival of sporangia of new clonal lineages of *Phytophthora infestans* in soil under semiarid conditions. *Plant Disease* 91: 835–841.

Porter, L.D., D.A. Inglis, and D.A. Johnson. 2004. Identification and characterization of resistance to *Phytophthora infestans* in leaves, stems, flowers, and tubers of potato clones in the Pacific Northwest. *Plant Disease* 88: 965–972.

Powelson, M.L., and D.A. Inglis. 1999. Foliar fungicides as protective seed piece treatments for management of late blight of potatoes. *Plant Disease* 83: 265–268.

Rotem, J. 1978. Climatic and weather influences on epidemics. Pages 317–338 in. Plant Disease, An Advanced Treatise. J.G. Horsfall and E. B. Cowling, eds. Academic Press, New York.

Rotem, J., and Y. Cohen. 1974. Epidemiological patterns of *Phytophthora infestans* under semi-arid conditions. *Phytopathology* 64: 711–7144.

Rotem, J., J. Palti, and J. Lomas. 1970. Effects of sprinkler irrigation at various times of the day on development of potato late blight. *Phytopathology* 60: 839–843.

Rotem, J., Y. Cohen, and J. Putter. 1971. Relativity of limiting and optimum inoculum loads, wetting durations, and temperatures for infection by *Phytophthora infestans. Phytopathology* 61: 275–278.

Rowlandson, T., M. Gleason, P. Sentelhas, T. Gillespie, C. Thomas, and B. Hornbuckle. 2015. Reconsidering leaf wetness duration determination for plant disease management. *Plant Disease* 99: 310–319.

Sunseri, M.A., D.A. Johnson, and N. Dasgupta. 2002. Survival of detached sporangia of *Phytophthora infestans* exposed to ambient, relative dry atmospheric conditions. *American Journal of Potato Research* 79: 443–450.

Sutton, J.C., T.J. Gillespie, and P.D. Hidebrand. 1984. Monitoring weather factors in relation to plant disease. *Plant Disease* 68: 78–84.

Thurston, H.D., K. Knutson, and C.J. Eide. 1958. The relation of late blight development on potato foliage to temperature and humidity. *American Potato Journal* 35: 397–406.

Van der Plank, J.E. 1963. Sanitation with special reference to potato blight. Pg. 122–136 in. Plant Diseases: Epidemics and Control. Academic Press, New York.

Wallin, J.R. 1962. Summary of recent progress in predicting late blight epidemics in United States and Canada. *American Potato Journal* 39: 306–312.

Wallin, J.R., and P.E. Waggoner. 1950. The influence of climate in the development and spread of *Phytophthora infestans* in artificially inoculated potato plots. *Plant Disease Reproduction Supplement* 190: 19–23.