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Effects of Temperature and Moisture Variables on Brown Rust Epidemics in Sugarcane

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Abstract

Epidemics of brown rust in sugarcane, caused by *Puccinia melanocephala*, vary in severity between seasons. Natural epidemics were studied to determine the effects of temperature and moisture variables on epidemic onset, severity and decline. Variables were monitored with disease severity in two cultivars, each grown at a different location in Louisiana. Maximum daily temperature was the variable most correlated with seasonal epidemic development and decline. Disease severity was high during 2009 and low during 2010. This contrast allowed evaluation of the effects of conducive and limiting environmental conditions on severity. Lower severity resulted from a combination of unfavourable temperature and leaf wetness conditions that delayed onset then reduced the rate of disease increase. An accumulation of 23–25 days with leaf wetness periods of at least 7 h after the daily minimum temperature exceeded 17°C preceded the onset of disease on young leaves in both severe and mild epidemics. Severe epidemics in both cultivars declined once maximum ambient daily temperature was 32°C or higher. Low and high limiting temperatures determined the initiation and decline of an epidemic, respectively, under Louisiana climatic conditions. The availability of leaf wetness was then an important determinant of disease severity during the epidemic.

Introduction

Brown rust caused by *Puccinia melanocephala* Syd. and P. Syd. is one of the most important diseases of sugarcane. Severe epidemics can cause yield reductions ranging from 10 to 50% in susceptible cultivars (Purdy et al. 1983; Comstock et al. 1992; Hoy and Hollier 2009). However, considerable year-to-year variation in brown rust epidemics occurs, and disease severity can be strongly affected by the interplay between the host, pathogen and environmental variables.

High temperatures have been linked to lower severity and the decline of epidemics. Thus, temperatures exceeding 35°C were reported to be limiting for infection under field conditions (Liu and Bernard 1979). Additionally, a significant reduction in the number of trapped urediniospores in spore samplers followed the occurrence of maximum daily temperatures above 30°C (Irey 1987). Long periods of leaf wetness and cool-to-warm temperatures have been reported as favourable for the development of brown rust (Bailey 1979; Raid and Comstock 2000). Long periods of warm and humid weather also were reported to be favourable for the disease (Sandoval et al. 1983). Mild winters have been linked to early outbreaks of brown rust during the growing season, most likely by allowing overwintering of the pathogen within the sugarcane fields (Irey 1987).

Historically, breeding and selecting resistant cultivars has been the sole means for brown rust management (Purdy et al. 1983; Raid and Comstock 2000). Unfortunately, the development of resistant cultivars is not a long-term solution for the problem because of the adaptability of *P. melanocephala*. The occurrence of races of this rust pathogen has not been extensively documented (Shine et al. 2005), but there have been numerous reports of cultivar shifts from resistance to susceptibility to brown rust (Dean and Purdy 1984; Raid 1989; Shine et al. 2005). In Louisiana, a shift from resistance to susceptibility was observed in the cultivar LCP 85-384, and severe to moderate symptoms have been observed in four previously resistant commercial cultivars that were released since 2003 (J. Hoy, unpublished data).

Replacing newly susceptible cultivars in the field is not an easy process in sugarcane even if suitable replacement cultivars are available. Vegetative propagation and a fallow period prior to planting make the planting process expensive. To recover costs, sugarcane growers must obtain multiple harvests from a single planting. Even if a suitable replacement cultivar is available, healthy seedcane supply may not be adequate for planting large areas. Sudden shifts to brown rust susceptibility in cultivars therefore have the potential to cause severe economic impact.

Fungicide application can provide an alternative management practice during periodic brown rust outbreaks (Hoy and Savario 2007). Spring epidemics can reduce cane yield by 10–20 tons/ha depending on the length of time it affects the crop (Hoy and Hollier 2009), but well-timed applications of fungicides can prevent this loss. However, fungicides are expensive, and rational use requires an understanding of the environmental conditions leading to severe epidemics.

Comprehensive knowledge of the epidemiology of brown rust under field conditions could provide the basis for a disease advisory system that would aid in decision making for the application and appropriate timing of chemical control. The objectives of this research were to determine the temperature and moisture conditions resulting in severe epidemics and assess the potential to formulate a disease advisory or field-level forecasting system for brown rust in sugarcane.

Material and Methods

Natural epidemics of brown rust were monitored in susceptible cultivars at two locations in 2009 and 2010. During 2009, a single field of cultivar Ho 95-988 (Tew et al. 2005) was monitored at the research farm of the USDA-ARS Sugarcane Research Unit in Schriever, LA (latitude 29.7126N, longitude −90.8273W), and a single field of cultivar LCP 85-384 (Milligan et al. 1994) was monitored at the Sugar Research Station of the Louisiana State University Agricultural Center in St. Gabriel, LA (latitude 30.257N, longitude −91.099W). Both cultivars were resistant to brown rust at the time of release but have since become susceptible. During 2010, a single field of Ho 95-988 was monitored at the USDA-ARS farm, and single fields of Ho 95-988 and LCP 85-384 were monitored at the Sugar Research Station.

Measurements were recorded and daily means determined for rainfall, upper leaf wetness (sensor at the top of the developing canopy), lower leaf wetness (sensor within the developing canopy), relative humidity (maximum, minimum and mean), temperature at the adaxial surface of an upper leaf (maximum, minimum and mean), temperature at the adaxial surface of a lower leaf (maximum, minimum and mean), and ambient air temperature (maximum, minimum and mean). Data for these variables were collected for the epidemic period during each season (3 April–16 July 2009; 4 April–17 July 2010).

Environmental variable data were recorded every 15 min with a single weather station (Watchdog, Model 700; Spectrum Technologies, Plainfield, IL, USA) arbitrarily located within each field. Temperature at the leaf surface and leaf wetness was measured for leaves at different positions on the plant. Data were taken for single leaves in −2 (upper) and +4 (lower) positions based on the Kuijper leaf numbering system for sugarcane (Clements and Ghotb 1968) in which leaves are assigned negative numbers acropetally and positive numbers basepitally relative to the youngest fully emerged leaf (with the collar joining the leaf blade and sheath visible). Leaf +4 is lower and partially shaded, while −2 is an upper, young leaf still emerging from the leaf whorl and fully exposed to the sky at the top of the developing canopy. Temperature was recorded with a thermocouple temperature sensor (Model 3667s; Spectrum Technologies). The lead for the sensor was attached to the adaxial leaf surface with adhesive tape. Leaf wetness sensors (grid-type electrical resistance, Model 3666, Spectrum Technologies) were placed at the level of −2 and +4 leaves. In preliminary monitoring with three sensors, temperature showed variation within 1.5°C and leaf wetness periods within 30 min, so only single leaves of each position were monitored in an individual field during the experiments. Leaves produced by the apical meristem emerge continuously through a leaf whorl at the shoot apex. Therefore, the temperature sensors on upper and lower leaves and heights of wetness sensors were adjusted weekly.

Brown rust was assessed on a weekly basis by arbitrarily collecting 15 leaves from different plants at the same position on the plant from a diagonal transect of each field. In severe brown rust epidemics, the young, recently emerged leaves with maximum photosynthetic potential become infected. Therefore, epidemic severity over time was monitored by collecting the second youngest (+1) fully emerged leaf at each weekly sampling within the fields. The leaves were scanned in their entirety using a CanoScan 8600F scanner (Canon Inc., Lake Success, NY, USA) to produce digital images that were analysed using Assess software to determine disease severity (percentage of the leaf area occupied by rust lesions). Weekly disease severity means were plotted to provide disease progress curves for the epidemic in each field.

Correlation analyses taking into consideration a symptom expression latent (lag) period of 8–14 days were conducted for each of the environmental variables with disease severity from 4 April up to the peak of the epidemic in each field for the two seasons (R-Statistical Program, R Foundation for Statistical Computing, Vienna, Austria). The analyses identified factors affecting the development of the epidemics.

The seasonal epidemic data sets for these variables were then compared to determine whether conducive or limiting values of these variables exhibited the potential to predict epidemic onset, progress and decline. A minimum of 7 h of leaf wetness and a minimum temperature of 17°C determined from controlled conditions experiments (Barrera et al. 2012) were employed as requirements for successful infection of sugarcane by *P. melanocephala*. The natural epidemic data sets were evaluated to determine whether a maximum temperature limiting infection could be identified.

Results

For the 2009 epidemic, sporulating pustules of brown rust were evident on plants of LCP 85-384 and Ho 95-988 during Spring by 4 April. However, disease did not begin to increase on the young, upper leaves until the week of 22 May in LCP 85-384 (Fig. 1) and the week of 29 May in Ho 95-988 (Fig. 2). Maximum disease severity was recorded on 12 June in LCP 85-384 with 35% of the leaf area exhibiting lesions and on 19 June in Ho 95-988 with 19%. After these dates, disease severity showed progressive reductions on new leaves in the same position on the plant. By 16 July, both cultivars had only 1.8% of leaf area affected by the disease. In 2010, disease did not develop during the spring on plants of LCP 85-384 and Ho 95-988 at St. Gabriel. Brown rust lesions were not detected on plants of Ho 95-988 at Shriever until 17 April, and disease severity on the upper leaves did not exceed 1% until 19 June (Fig. 3). Disease severity reached a maximum of 4% in the week of 10 July. The absence of disease in fields at the Sugar Research Station was related to a lack of primary inoculum, which was affected by the severity of the 2009–2010 winter freezes. This same factor delayed initial appearance of symptoms in cultivar Ho 95-988 in 2010 until 17 April, as opposed to the first observation of brown rust symptoms on 4 April in 2009.

Temperature records from a permanent weather station at the southernmost research farm in Shriever indicated that the 2009–2010 winter was much colder than the 2008–2009 winter. The total number of days with temperatures below freezing, the number of hours below freezing and lowest temperature were 17 days, 63 h and −2.8°C, respectively, for the 2008–2009 winter. In contrast, the same data were 27 days, 177 h and −7.2°C, respectively, for the 2009–2010 winter.

Environmental variables

The mean number of hours of leaf wetness per day was similar at the position of upper and lower leaves prior to epidemic onset and during the epidemic increase periods in LCP 85-384 (Fig. 1a) and Ho

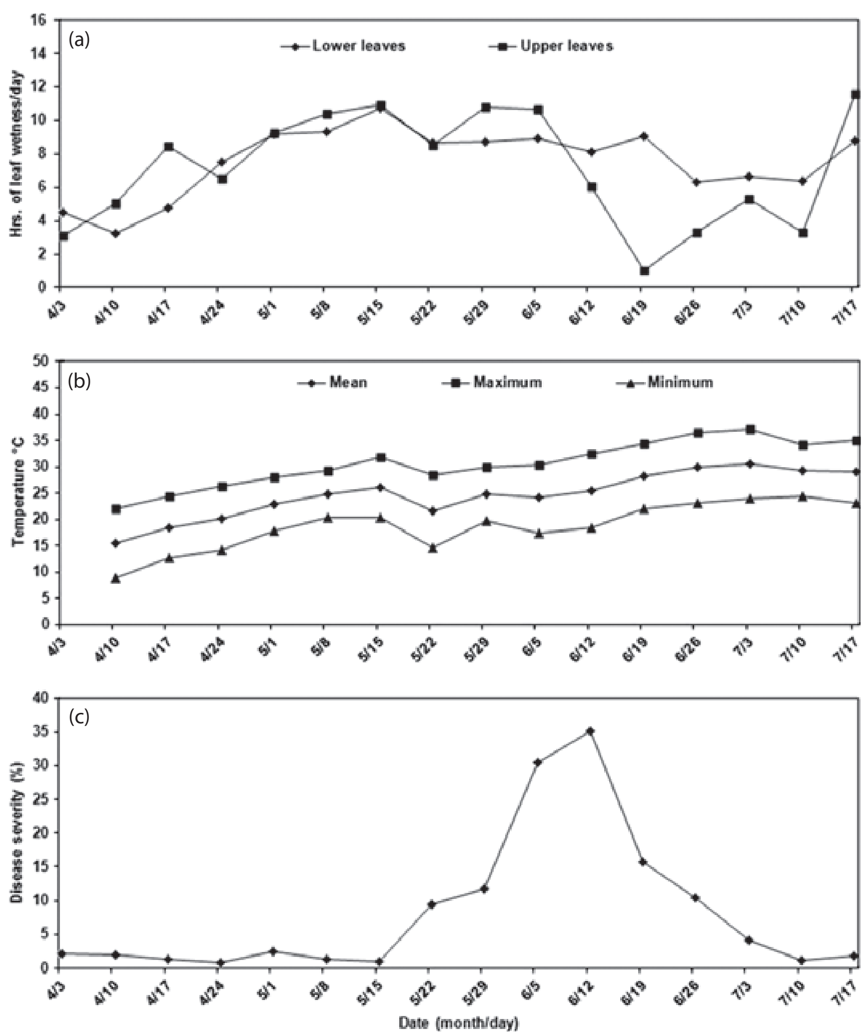

Fig. 1 Changes in leaf wetness, temperature and brown rust severity during the 2009 epidemic in cultivar LCP 85-384. (a) Weekly means for leaf wetness hours per day determined at the levels of upper and lower leaves. (b) Weekly means for mean, maximum and minimum daily ambient temperatures. (c) Disease severity (percentage of upper leaf area occupied by lesions)

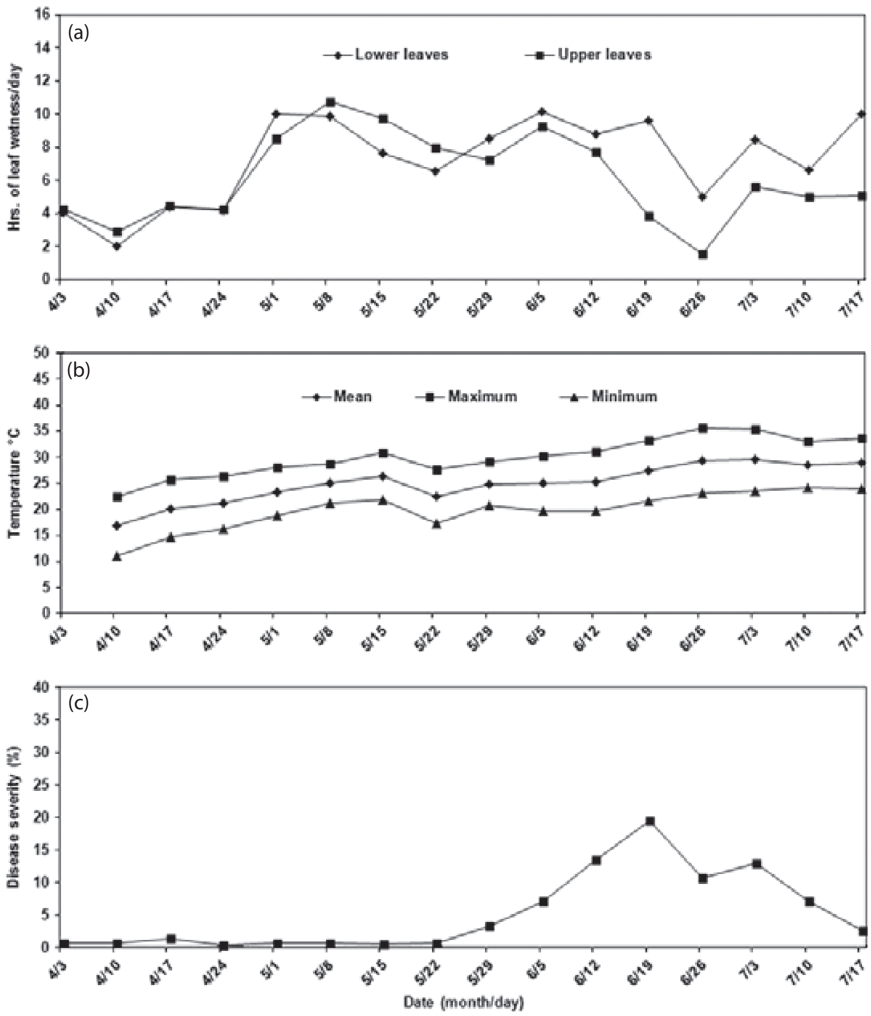

Fig. 2 Changes in leaf wetness, temperature and brown rust severity during the 2009 epidemic in cultivar Ho 95-988. (a) Weekly means for leaf wetness hours per day determined at the levels of upper and lower leaves. (b) Weekly means for mean, maximum and minimum daily ambient temperatures. (c) Disease severity (percentage of upper leaf area occupied by lesions)

95-988 (Fig. 2a) during 2009. The correlation coefficients between leaf wetness at the level of upper and lower leaves were 0.85 in LCP 85-384 and 0.77 in Ho 95-988. The correlation coefficient for leaf wetness on upper leaves in LCP 85-384 and Ho 95-988 was 0.78, while for lower leaves it was 0.79. Leaf wetness periods were longer on lower leaves as canopy cover increased. For the epidemic in LCP 85-384, the mean for leaf wetness period ranged between 8 and 11 h/day for 4 weeks prior to epidemic onset, continued at that level during the epidemic increase period on the upper leaves and dropped below 7 h/day on the upper leaves after 5 June (Fig. 1a). Brown rust severity on the upper leaves decreased rapidly after leaf wetness decreased. For the epidemic in Ho 95-988, the mean for wetness period ranged between 6 and 11 h/day for 4 weeks prior to onset, continued at that level during epidemic increase on the upper leaves and decreased below 5 h/day on the upper leaves after 12 June (Fig. 2a). As in LCP 85-384, epidemic severity decreased after the leaf wetness period decreased. During the 2010 epidemic in Ho 95-988, there was more variability between leaf wetness periods on upper and lower leaves (Fig. 3a). The mean for leaf wetness period ranged between 7 and 11 h/day on the upper leaves during 4 weeks prior to onset and between 7 and 15 h/day during the epidemic increase period. However, disease severity only ranged between 1 and 4% during this period. Epidemic severity began to decrease after the leaf wetness period decreased below 4 h/day.

Relative humidity exhibited low variation before, during, and after the epidemic period during 2009. The correlation coefficient for mean relative humidity during the epidemics in LCP 85-384 and Ho 95-988 was 0.89. Mean daily relative humidity ranged from 62 to 74% during the monitoring period at St. Gabriel in the field of LCP 85-384. At Shriever in the field of Ho 95-988, means for daily relative humidity only ranged from 81 to 83% during the experiment. Maximum relative humidity ranged from 90 to 100% in both fields for the entire experiment. Minimum relative humidity exhibited the highest variation. The average at St. Gabriel ranged from 29 to 53%, while at Shriever,

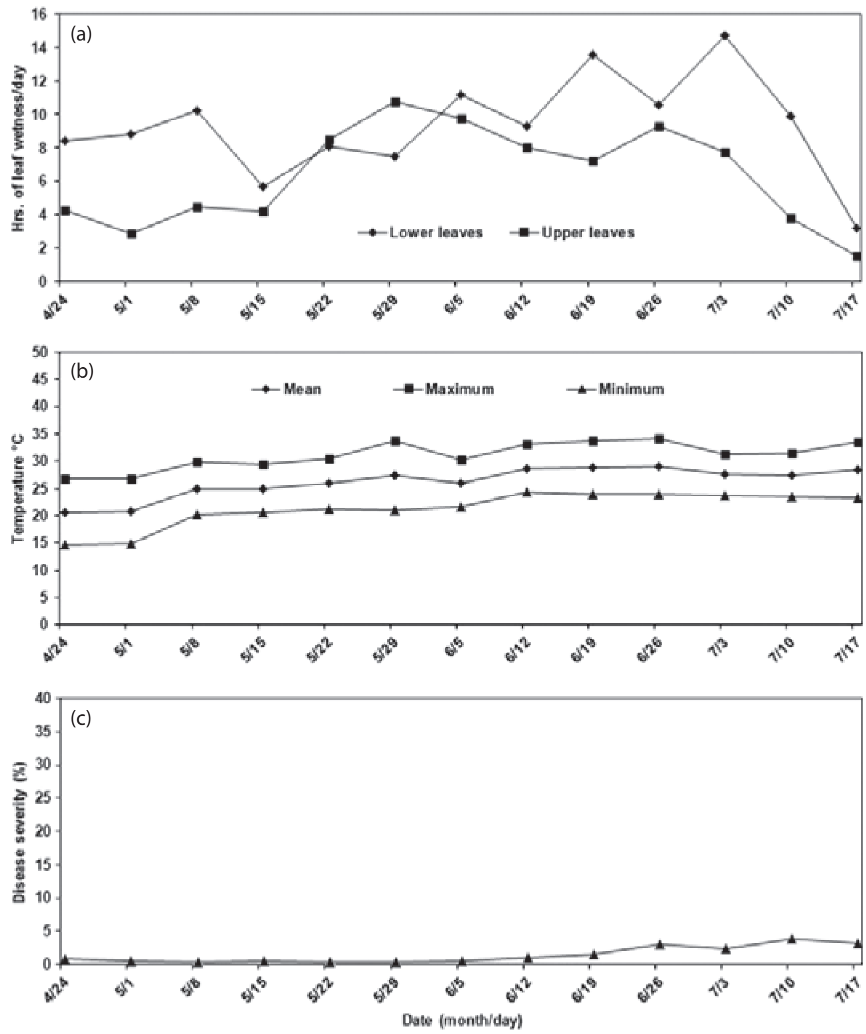

Fig. 3 Changes in leaf wetness, temperature and brown rust severity during the 2010 epidemic in cultivar Ho 95-988. (a) Weekly means for leaf wetness hours per day determined at the levels of upper and lower leaves. (b) Weekly means for mean, maximum, and minimum daily ambient temperatures. (c) Disease severity (percentage of upper leaf area occupied by lesions)

it ranged from 38 to 56%. During 2010, mean daily relative humidity exhibited only moderate variability during the experiment as in 2009 ranging from 74 to 91%. Minimum relative humidity exhibited the most variation ranging from 38 to 66%. Maximum relative humidity reached 100% nearly every day.

Low amounts of rainfall occurred during May and June of 2009. Weekly rainfall totals never exceeded 10 mm at St. Gabriel and 30 mm at Shriever. Only trace amounts of rain occurred at both locations during the peak of the epidemics. Rainfall was higher during the epidemic of 2010. Rainfall averaged more than 30 mm/week prior to epidemic onset and more than 80 mm/week during the epidemic.

Temperature patterns at the adaxial leaf surface were similar for both upper and lower leaves on the different cultivars at different locations. Correlation coefficients for temperatures on upper and lower leaves were 0.98 and 0.92 for LCP 85-384 and Ho 95-988, respectively. The correlation coefficient for temperature on upper leaves in LCP 85-384 and Ho 95-988 was 0.86, while for lower leaves the coefficient was 0.9. The week prior to the onset of the 2009 epidemics, minimum, mean and maximum daily temperatures averaged 19, 26–27 and 37–38°C, respectively. The week prior to the epidemic peaks, minimum, mean and maximum daily leaf temperatures averaged 17–20, 27–29 and 40–44°C, respectively. During the decline of the epidemics, minimum, mean and maximum daily temperatures averaged 22–24, 29–31 and 41–46°C, respectively. Temperature exhibited less variation during the monitoring period for the 2010 epidemic. Weekly averages for minimum, mean and maximum daily temperatures were 19–22, 26–30 and 38–50°C, respectively, during the onset, increase and decline of the epidemic.

Ambient temperatures gradually increased prior to the onset and during the increase of the 2009 epidemics. Ambient temperature showed low variation between locations with a correlation coefficient of 0.97. During the week of 15 May at the onset of the epidemic in LCP 85–384 at St. Gabriel, minimum, mean and maximum daily ambient temperatures were

20, 26 and 32°C, respectively (Fig. 1b). Ambient minimum, mean and maximum temperatures during the week of 22 May at the onset of the epidemic in Ho 95-988 at Shriever were 17, 22 and 28°C, respectively (Fig. 2b). Minimum, mean and maximum temperatures the week of the epidemic peak were 18, 25 and 32°C, respectively, at St. Gabriel and 22, 27 and 33°C, respectively, at Shriever. Slight additional temperature increases were associated with the decline of the epidemics. At St Gabriel, for the next 3 weeks, minimum values were 22, 23 and 24°C, while at Shriever they were 23, 24 and 24°C; likewise, the means at St. Gabriel were 28, 30 and 31°C, while at Shriever they were 29, 29 and 27°C; and for maximums, they were 34, 37 and 37°C at St. Gabriel, while they were 36, 35 and 33°C at Shriever. During the 2010 epidemic period, minimum, mean and maximum temperatures averaged 21–23, 25–29 and 29–33°C, respectively (Fig. 3b).

Correlation of environmental variables with disease severity

Environmental variables exhibited variable levels of correlation with brown rust severity within epidemics (Table 1). Maximum daily ambient air temperature was correlated with disease severity in LCP 85-384 during 2009, and maximum leaf temperature within the canopy was highly correlated with severity in Ho 95-988 in 2009. The slow, gradual increase in disease severity during the 2010 epidemic mirrored the gradual seasonal increase in temperature (Fig. 3) and rainfall, and this resulted in some significant correlation coefficients between temperature and moisture variables with severity.

Association of disease conducive and limiting environmental conditions with brown rust epidemic development and decline

The weekly mean for minimum daily temperature exceeded 17°C the week of 1 May for the 2009 epidemics and 8 May for the 2010 epidemic. An evaluation of the temperature data from the 2009 epidemics revealed that a weekly mean for daily maximum ambient temperature of 32°C or more preceded the decrease of disease severity. The number of infection limiting days per week with a maximum ambient temperature above 32°C varied during the 2009 and 2010 epidemics (Fig. 4a). During the 2009 epidemic in LCP 85-384 at St. Gabriel, the first two limiting days occurred the week of 15 May, one occurred the week of 29 May, two occurred the week of 5 June, then the number of disease limiting days increased to five the week of 12 June (the epidemic peak) and seven for the weeks of 19 June, 26 June and 7 July, as brown rust severity decreased to <2%. No days with limiting temperatures occurred during the 2009 epidemic in Ho 95-988 at Shriever until one was recorded the week of 5 June. Two limiting days occurred the next week, and then 3 weeks with continuous daily maximum temperatures above 32°C occurred beginning the week of 19 June (the epidemic peak). Disease severity decreased to <5% by mid-July. During 2010, hot weather occurred during the last week of May with seven infection limiting days occurring the week of 29 May. The number of limiting days ranged from 2 to 7 during June, and then 3 days with conducive temperatures occurred during the first 2 weeks of July when limited disease increase was observed.

The number of infection conducive days per week with more than 7 h of leaf wetness ranged from 0 to 7 from the last week of April until July during 2009 and from 3 to 7 during 2010 (Fig. 4b). The number of infection conducive days ranged from 4 to 7 days/week from the beginning of May until the week of 19 June during 2009 then decreased to four or less in late June and early July during the period of epidemic decline. The number of conducive days per week was more variable during the 2010 epidemic period. The number of conducive days ranged from 3 to 6 days/week

Table 1
Correlation analysis comparing all variables with disease severity for two cultivars, LCP 85-384 and Ho 95-988, during the 2009 and 2010 brown rust epidemics

	LCP 85-384 (2009) at St. Gabriel		Ho 95-988 (2009) at Shriever		Ho 95-988 (2010) at Shriever	
Variables	Correlation coefficient	P-value	Correlation coefficient	P-value	Correlation coefficient	P-value
Leaf wetness on lower leaf (h/day)	0.26	0.43	0.45	0.17	0.86	<0.01
Leaf wetness on upper leaf (h/day)	0.48	0.15	0.26	0.44	0.32	0.33
Relative humidity (daily mean)	0.02	0.94	0.16	0.67	0.73	0.01
Relative humidity (daily minimum)	−0.14	0.77	−0.07	0.88	0.56	0.08
Relative humidity (daily maximum)	0.44	0.23	0.42	0.23	0.25	0.46
Rainfall per day	−0.18	0.74	−0.08	0.83	0.90	<0.01
Temperature on lower leaf (daily mean)	0.33	0.35	0.54	0.11	0.47	0.15
Temperature on lower leaf (daily minimum)	0.40	0.29	0.28	0.53	0.70	0.02
Temperature on lower leaf (daily maximum)	0.47	0.19	0.74	0.01	−0.30	0.36
Temperature on upper leaf (daily mean)	0.40	0.26	0.47	0.17	0.50	0.22
Temperature on upper leaf (daily minimum)	0.30	0.40	0.31	0.38	0.92	<0.01
Temperature on upper leaf (daily maximum)	0.13	0.71	0.56	0.09	0.25	0.54
Ambient temperature (daily mean)	0.38	0.28	0.42	0.23	0.62	0.04
Ambient temperature (daily minimum)	0.23	0.51	0.30	0.41	0.65	0.03
Ambient temperature (daily maximum)	0.67	0.05	0.56	0.09	0.55	0.08

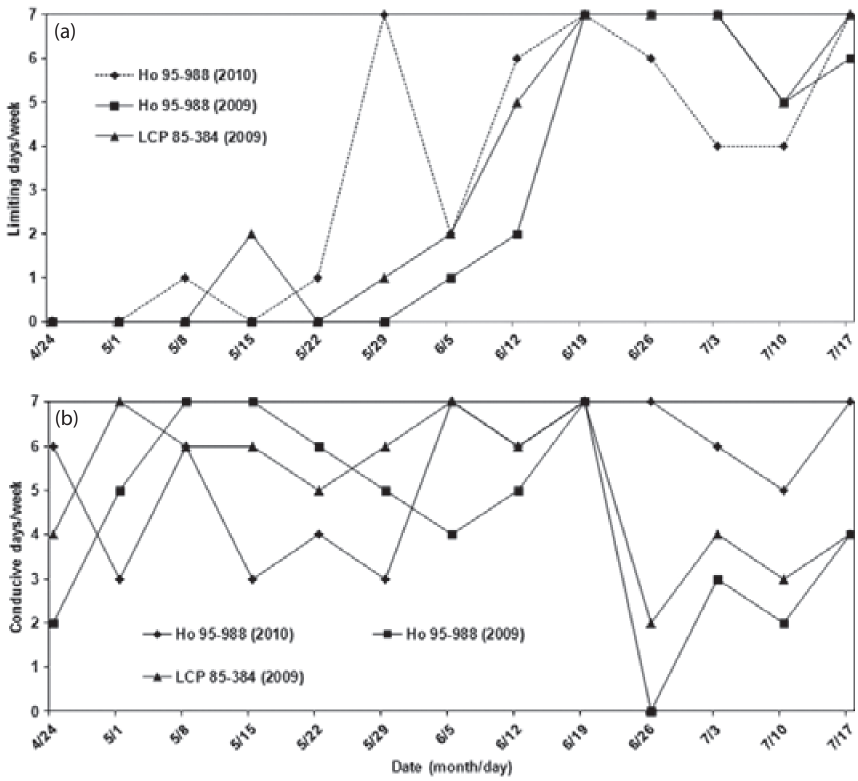

Fig. 4 Occurrence of temperature and leaf wetness conditions limiting or conducive, respectively, for brown rust development during the 2009 and 2010 epidemics. (a) Days per week with maximum ambient temperature above 32°C; (b) Number of days per week with seven or more leaf wetness hours on upper leaves

during May then ranged from 5 to 7 during June and July when limited disease increase was occurring.

The cumulative number of infection conducive days occurring during each epidemic after the minimum temperature was reached until disease onset on upper leaves was determined for leaf wetness and temperature (Table 2). The cumulative number of temperature conducive days ranged from 21 to 33 days among the three epidemics. It was least for the epidemic in LCP 85-384 (2009) with the earliest start date and progressively greater for the Ho 95-988 (2009) epidemic that began a week later and the 2010 epidemic that did not begin on the upper leaves for another 3 weeks. However, the cumulative number of conducive leaf wetness days until epidemic onset was similar for each of the three epidemics, ranging from 23 to 25 days. Leaf wetness conducive days preceding the epidemics were 23, 25 and 25 for LCP 85-384 (2009), and for Ho 95-988 in 2009 and 2010, respectively.

Table 2
Cumulative days with leaf wetness and temperature conditions conducive for infection after the first occurrence of minimum daily temperatures required for infection until brown rust epidemic onset in 2009 and 2010 in two susceptible cultivars

		Cumulative disease conducive days	
Cultivar	Epidemic	Leaf wetness[a]	Temperature[b]
LCP 85-384	2009	23	21
Ho 95-988	2009	25	28
Ho 95-988	2010	25	33

[a]Disease conducive day = at least 7 h of leaf wetness per day.
[b]Disease conducive day = mean ambient temperature between 17 and 30°C.

Discussion

The severity of the 2009 brown rust epidemic in two different cultivars at different locations indicated that seasonal conditions were conducive for severe disease development. The time course of the disease progress curves was similar for the epidemics in both cultivars. The two cultivars included in the study are now both rated as susceptible to brown rust, but they vary in phenotypic characteristics. LCP 85-384 is characterized as having a smaller stalk diameter, high stalk population and narrow upright leaves (Milligan et al. 1994). Ho 95-988 differs from LCP 85-384 in having a larger stalk diameter, lower stalk population, broader leaves and drooping leaf blade (Tew et al. 2005). Despite these morphological differences, similar brown rust epidemics developed in both cultivars. This suggested that cultivar phenotype is not a major factor affecting the development of brown rust epidemics. If environmental factors result in the development of severe epidemics that are similar across susceptible cultivars, this could allow the use of only weather information in the formulation of disease advisory or forecasting systems.

The same combination of factors affected disease increase in 2009 and 2010. However, disease severity was lower in the 2010 brown rust epidemic. This difference offered the opportunity to examine the impact of conducive or limiting values for individual variables on disease increase and determine their relative importance.

Epidemics of brown rust increase then decline within the first half of the sugarcane growing season. An analysis of all the factors involved was undertaken to better elucidate what determines the epidemic period and then the combination of factors during the epidemic period that determine severity. Conditions conducive for infection and disease increase must develop and persist then the occurrence of non-conducive or limiting conditions result in the decline of the epidemic.

For many fungal foliar pathogens, successful infection depends on the occurrence of an adequate duration of leaf wetness under favourable temperatures (Huber and Gillespie 1992). Successful brown rust infection was previously considered to require at least 8 h of wetness (Raid and Comstock 2000). Results from controlled conditions experiments (Barrera et al. 2012) indicated that successful infection of Ho 95-988 leaves occurred after exposure to 7 h of leaf wetness.

The field study results suggest that the climate in Louisiana results in the occurrence of dew formation sufficient to provide brown rust conducive leaf wetness conditions during the spring by mid- to late-April that then persist during the epidemic period. During the 2009 epidemics, there were five or more days per week with seven or more hours of leaf wetness from the last week of April until mid-June. The occurrence of 3 weeks with only 3–4 conducive days during May might have delayed the 2010 epidemic start. This observation is also supported by the similar number of leaf wetness conducive days prior to the onset of epidemics in both years. The results suggest there may be a requirement for cumulative leaf wetness conducive days before the epidemic develops on the young leaves of plants in a field and that leaf wetness is an important determining factor for brown rust severity during the epidemic period in Louisiana.

Conditions highly favourable for dew formation frequently occur during the spring in Louisiana; however, the occurrence of rain is more variable. The effect of rain on brown rust epidemics has not been conclusively determined previously. A detrimental effect has been suggested, as rain has the potential to remove spores from the leaf surface (Raid and Comstock 2006). The 2010 epidemic with lower disease severity was characterized by higher amounts of rain during the epidemic compared with 2009.

Temperature can affect the availability of primary inoculum and the number of secondary infection cycles during an epidemic. Thus, it can affect inoculum availability, the time of epidemic onset, the rate of disease increase and the eventual decline of the epidemic.

Sugarcane is grown in Louisiana at the northern limit of its cultivation range at 30°N latitude. Variation in the occurrence of freezing conditions during winter can affect the overwintering of *P. melancephala* by determining the extent of survival of living leaf tissue infected by the fungus. Brown rust lesions were first observed on lower leaves by 4 April following the mild 2008–2009 winter, whereas disease was not detected following a severe winter until 13 days later and only at the southernmost location in 2010. An epidemic did not develop on young leaves of both susceptible cultivars during 2010 at St. Gabriel, the northernmost location in the study. Additional comparisons of hours below freezing during winter and the onset of brown rust epidemics may allow the development of a guideline for inclusion in a disease severity advisory that would more accurately predict the threat of a severe epidemic in susceptible cultivars.

The date of first infection would be affected by the availability of primary inoculum and the development of temperatures conducive for infection as the season changes and the sugarcane growing season begins. Under controlled conditions, temperatures reported to be conducive for infection ranged from 17 to 27°C (Barrera et al. 2012), 15 to 30°C (Sotomayor et al. 1983) and 21 to 26°C (Sahni and Chona 1965). A mean minimum temperature of 17°C did not occur until the week ending 1 May in 2009 and 8 May in 2010.

Temperature can determine when it is possible for a brown rust epidemic to begin and determine when it begins to decline. Temperature eventually becomes limiting for continued disease increase. However, it is uncertain how this is accomplished. Temperatures during the night when leaf wetness is present could affect the success of the infection process, but the daily minimum temperature during the epidemic period was within the range favourable for infection during both the 2009 and 2010 epidemics. Under controlled conditions (Barrera et al. 2012), a constant temperature of 31°C inhibited infection of Ho 95-988 leaves. A comparison of the field data sets suggested that a daily ambient maximum temperature of 32°C or above was inhibitory to disease increase. The temperature at the leaf surface can be higher than ambient temperature, and maximum daily temperatures exceeded 40°C during the decline of the 2009 epidemics and during the course of the less severe 2010 epidemic. The infection process may be affected by temperature at the leaf surface, but ambient temperature is more easily measured. Lower maximum ambient temperatures in early July may have allowed the continuation of the 2010 epidemic at a low level.

High temperatures can adversely affect urediniospore germination, appressorium formation and establishment of infection (Sotomayor et al. 1983). Urediniospores lose the ability to germinate after 5 days when exposed to 30°C (Sandoval et al. 1980) and rapidly lose viability during hot weather with temperatures above 35°C (Purdy et al. 1983). The detrimental effect of high temperatures on urediniospore viability under field conditions could constitute an important determining factor for the decline of epidemics. Lower amounts of urediniospores were collected by spore traps following maximum daily temperatures above 30°C (Irey 1987). The negative effect of high temperatures on brown rust severity also has been reported previously. Lower levels of disease were observed in the Dominican Republic when temperatures exceeded 35°C (Liu and Bernard 1979).

Longer periods of leaf wetness can expand the range of temperatures conducive for infection (Barrera et al. 2012). Field evidence for this can be found in the 2010 epidemic. Weeks with daily leaf wetness period means of approximately 14 h occurred the week before the two epidemic peaks during July. The abundant leaf wetness may have allowed the epidemic to continue at a low level despite the occurrence of unfavourable high temperatures.

Yield loss due to brown rust is a function of the length of the epidemic and the level of severity reached on the young leaves (Hoy and Hollier 2009). Disease severity on young leaves of LCP 85-384 was 15% by 15 April during 2004 when the documented yield loss was higher than in other annual epidemics that began later. An understanding of factors affecting the onset and decline of epidemics could allow the formulation of a disease forecasting system that prevents potential losses by timing fungicide applications. This study provided data sets for environmental variables and disease progress that allowed the more accurate delineation of conditions conducive or limiting for brown rust increase that determine seasonal epidemic severity. The results suggest that an epidemic will not begin on the young leaves until 23–25 days with conducive leaf wetness have occurred after temperatures favourable for infection exist in the field. Continuing leaf wetness and temperature conditions favourable for disease will allow the epidemic to persist and increase in severity on the continuously emerging leaves. The epidemic will continue until daily temperature maximums consistently exceed 32°C in late May or by mid-June, and the epidemic will then decline during the summer season. As moisture and temperature conditions during the epidemic period are generally favourable for infection, the length of the epidemic period is an important determinant of severity and potential yield loss.

The data obtained in this study suggest that the development of a disease advisory based primarily on ambient temperature as a measure of winter severity, the first occurrence of favourable conditions, and the transition to limiting conditions could predict potential for a severe epidemic and the time period when fungicide application might be needed. The use of cumulative disease conducive leaf wetness days following the occurrence of favourable minimum temperatures for predicting epidemic onset needs further evaluation, but this parameter has the potential to contribute to a forecaster that would allow the economic use of fungicides for brown rust management. The utility of the environmental conditions identified in this study for the prediction of severe brown rust outbreaks needs to be confirmed in additional epidemics.

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References

Bailey RA. (1979) Sugarcane rust in South Africa. *Sugarcane Pathol Newsl* **22**:12–13.

Barrera WA, Hoy JW, Li B. (2012) Temperature and leaf wetness effects on infection of sugarcane by *Puccinia melanocephala*. *J Phytopathol* **160**:294–298.

Clements HF, Ghotb A. (1968) The numbering of leaves and internodes for sugarcane nutrition studies. *Proc Int Soc Sugar Cane Technol* **13**:569–584.

Comstock JC, Shine JM, Raid RN. (1992) Effect of sugarcane rust on growth and biomass. *Plant Dis* **76**:175–177.

Dean JL, Purdy LH. (1984) Races of the sugarcane rust fungus, *Puccinia melanocephala*, found in Florida. *Sugar Cane* **1984**:15–16.

Hoy JW, Hollier CA. (2009) Effect of brown rust on yield of sugarcane in Louisiana. *Plant Dis* **93**:1171–1174.

Hoy JW, Savario CF. (2007) Can fungicides provide an alternative control measure for brown rust? *J Am Soc Sugar Cane Technol* **27**:60.

Huber L, Gillespie TJ. (1992) Modeling leaf wetness in relation to plant disease epidemiology. *Annu Rev Phytopathol* **30**:553–577.

Irey M. (1987) Effect of the environment on sugarcane rust epidemics in Florida. *J Am Soc Sugar Cane Technol* **7**:30–35.

Liu LJ, Bernard F. (1979) Sugarcane rust in the Dominican Republic. *Sugarcane Pathol Newsl* **22**:5–7.

Milligan SB, Martin FA, Bischoff KP, Quebedeaux JP, Dufrene EO, Quebedeaux KL, Hoy JW, Reagan TE, Legendre BL, Miller JD. (1994) Registration of 'LCP 85-384' sugarcane. *Crop Sci* **34**: 819–820.

Purdy LH, Liu LJ, Dean JL. (1983) Sugarcane rust, a newly important disease. *Plant Dis* **67**:1292–1296.

Raid RN. (1989) Physiological specialization in sugarcane rust (*Puccinia melanocephala)* in Florida. *Plant Dis* **73**:183.

Raid RN, Comstock JC. (2000) Brown rust. In: Rott P, Bailey RA, Comstock JC, Croft BJ, Saumtally S. (eds) *A Guide to Sugarcane Diseases*. Montpellier, Cirad, pp 85–89.

Raid RN, Comstock JC. (2006) *Sugarcane Rust Disease*. Agronomy Department document SS-AGR-207. Gainesville, FL, USA, University of Florida/IFAS.

Sahni ML, Chona BL. (1965) Studies on sugarcane rust in India. *Indian Phytopathol* **18**:191–203.

Sandoval I, Cuello L, Picornell V. (1980) Studies of some biological aspects of the sugarcane rust producing fungus in Cuba. *Cienc Tec Agric, Cana de Azucar* **2**:105–107.

Sandoval I, Picornell V, Chaves R, Ramos N. (1983) Puccinia melanocephala H&P. Syd.: biological and ecological aspects. *Proc Int Soc Sugar Cane Technol* **18**:845–853.

Shine JM Jr, Comstock JC, Dean JL. (2005) Comparison of five isolates of sugarcane brown rust and differential reaction of six sugarcane clones. *Sugar Cane Int* **23**:24–29.

Sotomayor IA, Purdy LH, Trese AT. (1983) Infection of sugarcane leaves by *Puccinia melanocephala*. *Phytopathology* **73**:695–699.

Tew TL, Burner DM, Legendre BL, White WH, Grisham MP, Dufrene EO, Garrison DD, Veremis JC, Pan Y-B, Richard EP Jr. (2005) Registration of 'Ho 95-988' sugarcane. *Crop Sci* **45**:1660.