The Microclimate in Tall Fescue Turf as Affected by Canopy Density and Its Influence on Brown Patch Disease

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ABSTRACT

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Microenvironment was monitored within tall fescue (*Festuca arundinacea*) experiment plots in which the severity of brown patch disease, caused by *Rhizoctonia solani* AG-1-IA, was found to correlate with canopy density. Canopy density was varied either by planting cultivars that produced different densities, or by planting a single cultivar at three seeding rates. Air and foliage temperatures within the canopy differed by only approximately 1°C between low- and high-density canopies during 1993 and 1994 in both studies. In a wet year, 1993, leaf wetness and relative humidity did not differ significantly between low- and high-density canopies. In 1994, which was more typical in regards to weather, a denser canopy promoted leaf wetness and high relative humidity in both studies. Leaf wetness duration averaged over 10 days was 0.8 h longer in the high-density cultivar Arriba than in the low-density cultivar Fawn. In addition, the period of relative humidity above 90% was 2.3 h longer in Arriba than in Fawn. Canopies of tall fescue with different plant densities were inoculated in the laboratory with *R. solani* and placed under uniformly high humidity and temperature. Hyphae grew between leaf blades separated by up to 8 mm. Interblade hyphal growth occurred more frequently in high-density canopies because of the closer proximity of leaf blades, and as a result, mycelia and necrosis spread more rapidly from inoculation sites in high-density canopies. It was concluded that microenvironmental conditions and the physical proximity of leaf blades in high-density turfs can be more favorable for brown patch disease.

Higher canopy density, as measured by the number of leaf blades per unit area and by verdure, was found to be associated with increased severity of brown patch disease, caused by *Rhizoctonia solani* Kühn AG-1-IA, in tall fescue (*Festuca arundinacea* Schreb.) turf under field conditions (5,12). This effect was hypothesized to be due in part to more disease-favorable microenvironmental conditions occurring in the canopies of high-density turfs. The effects of plant density and architecture on canopy microenvironmental conditions, and subsequently on disease, have been shown in other cropping systems. For example, thinned carrot canopies generally had one-third fewer hours with relative humidity above 95%, and this was associated with reduced southern blight caused by *Sclerotium rolfsii* Sacc. (8). In another example, conditions within an open canopy of a common bean (*Phaseolus vulgaris* L.) cultivar with an upright habit were warmer and drier than within a cultivar with a more dense, viney canopy structure (1); this was related to a lower severity of white mold disease caused by *Sclerotinia sclerotiorum* (Lib.) de Bary in the open canopy. Temporal changes in a crop canopy can also regulate epidemics. Aerial blight of soybean, caused by *R. solani* AG-1-IA, was found to occur in two phases (10). The first phase, the initial infection of foliage by the fungus, occurred before canopy closure. The second, spread from the initial infections, occurred only after canopy closure and was attributed in part to prolonged leaf wetness after canopy closure (10).

Another possible mechanism for the observed relationship between tall fescue canopy density and brown patch disease severity is that the proximity of blades within a high-density turf facilitates spread of the pathogen by hyphal growth. Sclerotia and infected host tissue are the primary inoculum for *R. solani* in turfgrass (2). Subsequent expansion of infection foci occurs by mycelial growth through the canopy or by the dissemination of infected cut blades. The fungus has been shown to grow on grass blades in advance of symptoms (13) at or above 95% relative humidity (11). The ability of the fungus to bridge the distances between blades within a turfgrass canopy could be a factor affecting disease severity.

The goal of this study was to investigate the role of canopy density and microenvironment in the development of disease in the field. One objective was to compare microenvironmental conditions within tall fescue canopies that varied in density and sustained different levels of brown patch disease (5). The second objective was to test whether physical leaf blade proximity, as determined by plant density, could affect pathogen growth and disease development.

MATERIALS AND METHODS

Monitoring the microenvironment in the field. A microenvironmental monitoring system (Fig. 1) was used to measure leaf wetness, relative humidity, canopy air temperature, and foliage temperature within tall fescue turf canopies. Impedance sensors (4), which were modifications of a design reported by Fernandes et al. (3), were used to detect leaf wetness. Each had a pair of minute probe pins, separated by 5 mm, that were inserted into a leaf blade (Fig. 1B). Three leaf wetness sensors were placed 3 cm above the soil in each plot. Relative humidity and canopy air temperature were measured with an aspirated system, manufactured by REBS, Inc., Seattle, WA, placed in the center of each plot. This system consisted of a platinum resistance temperature detector with 100 ohm resistance and a psychrometer (Model HMP 35D, Vaisala, Inc., Woburn, MA). The instrument was 3 cm above the canopy rather than in the canopy, in order to sample air from a wider turf area and minimize disruption of canopy conditions. Foliage temperature was measured with an infrared temperature sensor (Model 4000AL, Everest, Inc., Fullerton, CA) set at 87-cm height and at a view zenith angle of 45° facing south. Total incoming solar radiation was measured with a pyranometer (Model LI-200SZ, Licor, Inc., Lincoln, NE). Wind speed was measured with a three-cup anemometer (Model 010B, Met-One Instruments, Grants Pass, OR) at 1 m above the canopy. Data were recorded with Omnidata 900 series loggers (Omnidata Int., Ogden, UT) with scans taken every minute and averaged every 10 min.

Microenvironmental conditions were measured in two sets of tall fescue field experiment plots (5) in which higher brown patch disease levels were found in canopies with greater blade density and verdure. In one set, cultivars of tall fescue were planted in 1992 in 3.0 × 6.1 m plots replicated four times in a randomized

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complete block design. Microenvironmental monitoring instrumentation was placed in cv, Fawn, which had a low canopy density, and in cv. Arriba, which had a high canopy density. The two cultivars differed in resistance to an *R. solani* isolate in growth chamber tests (12), but differences in disease levels measured in the field were unrelated to resistance (5). Measurements were made from 29 August to 4 September 1993 and from 5 August to 21 August 1994. Leaf wetness data were not collected in 1993.

In the second set of plots, three canopy densities were established by seeding Fawn tall fescue at 10, 30, and 50 g of seed per m^2 on 26 May 1993. There were four replicate plots of 3.0 × 4.5 m in a randomized complete block design. Measurements were made from 2 August to 17 August 1993 and from 30 August to 4 September 1994. Leaf wetness was determined only in the low- and high-canopy-density turfs. Otherwise, microenvironmental measurements were made in all three canopy densities.

These field studies were located at the John Seaton Anderson Turfgrass Research Facility near Mead, Nebraska (41°09′N; 96°30′W, alt. 366 m). All plots were maintained at 8 cm by weekly mowings with clipping removal. Sprinkler irrigation was applied twice daily between 1900 and 2400 h for 10-min intervals each to supply 3.8 cm of water per week. Plots were fertilized monthly from May through October with 50 kg of N per ha.

Instrumentation was available to monitor only one complete block at a time and therefore was moved from one block to another at 3- to 6-day intervals immediately after mowing. Data from at least two blocks, each with 1 to 6 days of measurements, were used in the statistical analysis. Leaf wetness measurements from days in which there was precipitation were excluded. The data were analyzed by first calculating summary statistics (maximum, minimum, average, and the range between minimum and maximum) for each 24-h period beginning at 1700 h. Relative humidity also was analyzed by calculating how long relative humidity above 90% occurred within each 24-h period. This humidity level was considered the threshold for growth of *R. solani* based on an average of reported minimum humidities required for growth of *R. solani* isolates (11,14) minus a sensor error of 3% for relative humidity measurements greater than 90%. Leaf wetness measurements were used to determine onset and ending times and to calculate daily leaf wetness durations. The summary data then were analyzed using analysis of variance of a randomized complete block design, with dates being considered subsamples. In the analysis, date was treated as a nested parameter within spatial blocks, and the treatment by block error term was applied. Least square means were calculated, and the LSD test was used for mean separation. Treatment differences at the 90% confidence level were considered to be significant. All statistical procedures were performed with Statistical Analysis Software (SAS Institute, Cary, NC) using the Proc GLM option.

Evaluation of hyphal growth at different canopy densities. The effects of the physical proximity of leaf blades on pathogen growth and disease development

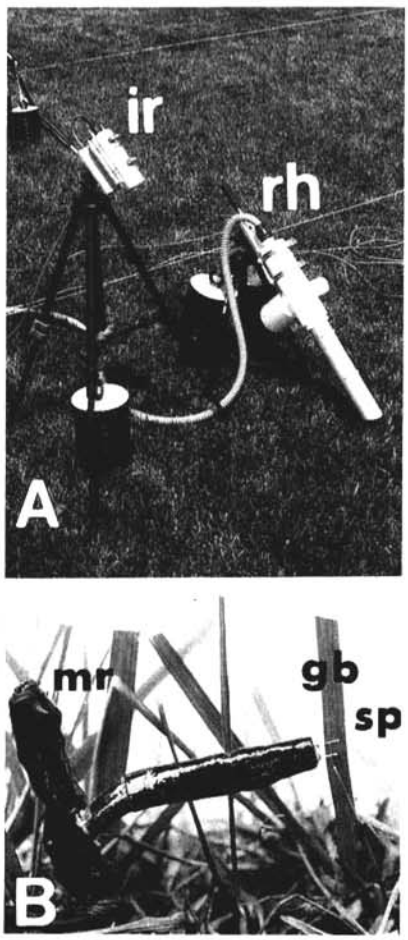

Fig. 1. Microenvironmental monitoring system used to measure conditions in tall fescue canopies. **(A)** Apparatus for drawing canopy air across relative humidity and temperature sensors (rh), and infrared thermometer (ir) for measuring foliage temperature; **(B)** Leaf wetness sensor used to measure conditions at 3-cm height from the soil surface: sensor probe pins (sp) inserted into grass leaf blade (gb), and mounting rod (mr) with base inserted into soil. For scale, the distance between sensor probe pins is 5 mm.

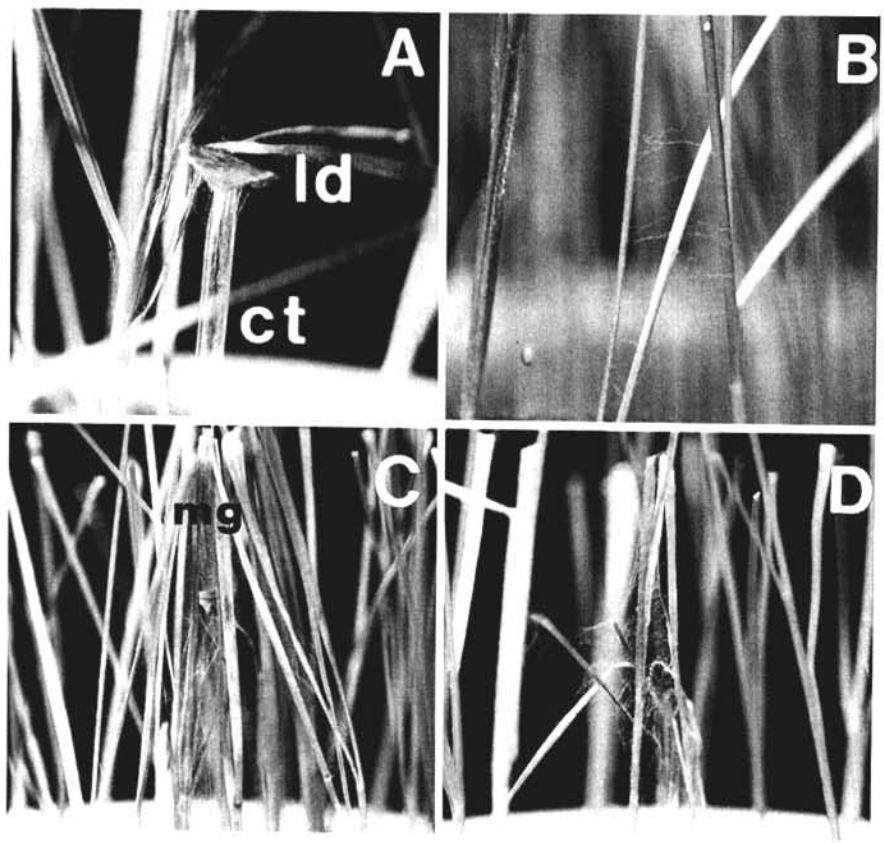

Fig. 2. Tall fescue canopy density effects on interblade growth of *Rhizoctonia solani* hyphae and necrosis development under controlled environmental conditions. **(A)** Method used in inoculating seedlings of tall fescue Fawn: *R. solani* infected leaf disk (ld) and capillary tube (ct) used to suspend leaf disk at 3 cm height within the canopy of seedlings (2.4×). **(B)** Growth of *R. solani* mycelium between tall fescue leaf blades (2.4×). **(C)** Hyphal growth and necrosis in a high-seedling-density canopy. Mycelial growth resulted in a matting of grass blades (mg) surrounding the leaf disk inoculum (1.8×). **(D)** Hyphal growth and necrosis in a low-seedling-density canopy (1.8×).

were investigated in growth chamber experiments. Fawn was seeded at 10 or 50 g of seed per m^2 into 150-ml plastic cups. The growth medium was a pasteurized mixture of equal parts vermiculite, sand, and Sharpsburg silty-clay loam. Following germination, seedlings were maintained at 25°C under 16-h fluorescent light (10 W/m^2). At 12 days, seedlings were clipped to 5-cm height. The distances between leaf blades were measured with a millimeter ruler for 10 pairs of leaf blades per cup. Each cup was inoculated by suspending an infected piece of leaf tissue on the end of a capillary tube placed in the center of each canopy (Fig. 2A). The infected leaf piece consisted of a 5-mm-diameter disk cut from a mature tall fescue leaf blade that had been inoculated with *R. solani* isolate R251 and cultured on water agar for 4 days at 25°C. Individual cups were placed in a large plastic tub with a clear plastic top. Water was added to the bottom of the tub to generate high relative humidity. The tub was then placed in a growth chamber maintained at 28°C with 12-h lighting. Every 24 h for 4 days, the focus diameter (the horizontal distance along a transect through the leaf disk at which hyphae occurred) was measured using a millimeter ruler and a 10× hand lens. Two measurements were made per cup and averaged. Observations also were made of the maximum distance between blades bridged by the fungus hyphae. The percentage of foliage with necrosis was visually assessed 4 days after inoculation. There were six to 11 replicate cups per treatment, and the experiment was performed three times.

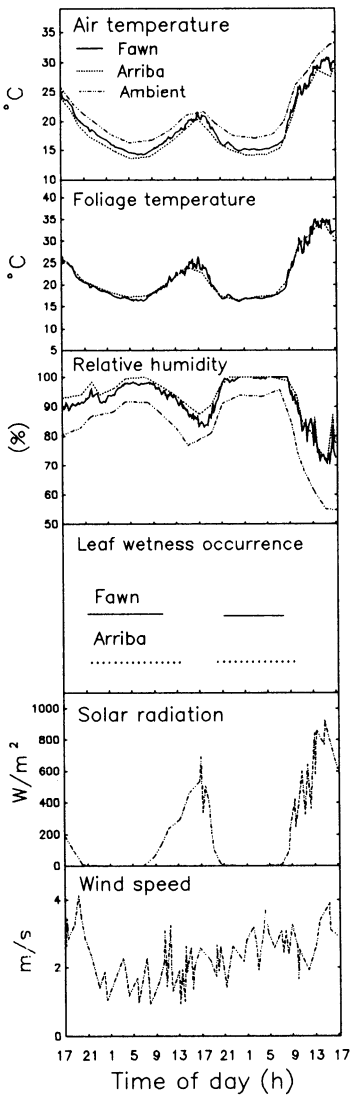

Fig. 3. Environmental conditions measured in the canopies of a high-density tall fescue cultivar Arriba and a low-density cultivar Fawn, and in the ambient air over two 24-h periods starting at 1700 h on 10 August 1994. Lines for leaf wetness occurrence indicate actual times of occurrence.

RESULTS

Effects of canopy density on canopy microclimate. Microenvironmental differences were found between canopies differing in density in both field experiments. Generally, differences in microenvironmental conditions were subtle, except for leaf wetness and relative humidity. This is illustrated in Figure 3, which shows data from the cultivar experiment measured on an overcast day, as indicated by lower solar radiation, followed by data from a clear day, when solar radiation peaked at 990 W/m^2. Wind speed patterns on these 2 days were different, with generally greater speeds occurring on the clear day and more variation occurring on the overcast day. Foliage and canopy air temperatures ranged from 13 to 25°C on the overcast day and from 14 to 35°C on the clear day. Foliage temperatures were virtually identical between the two cultivars. Canopy air temperatures tended to be 1 to 4°C lower than ambient air temperatures and also were similar for both cultivars. The low-density Fawn canopy generally was 1°C warmer. Relative humidity in the canopies was 5 to 15% higher than ambient. On the overcast day, canopy relative humidity dropped to a minimum of 80%, in contrast to 68% on the clear day. Relative humidity in the high-density canopy tended to be higher by up to 5%. The number of hours of relative humidity above 90% was generally greater in the high-density canopy. Leaf wetness was prolonged in the high-density cultivar, with a 1.5-h-longer leaf wetness duration occurring in the high-density canopy on the clear day.

The same microenvironmental trends were evident when measurements were considered over the entire duration of the study each year. Air temperatures generally were higher in the low-density canopies than in the high-density canopies in both the cultivar and Fawn seeding rate experiments, but the level of difference varied among years and experiments. Greater differences between canopies were measured in the cultivar experiment (Table 1) and were statistically significant ($P < 0.10$) for all canopy air temperature parameters (maximum, minimum, mean, and range) in 1993 and for average and range in 1994. The maximum air temperature in the low-density cultivar Fawn was 1.7 to 2.1°C higher than in the high-density cul-

Table 1. Summary of temperature and relative humidity conditions[a] measured in tall fescue cultivars Fawn (low canopy density)[b] and Arriba (high canopy density)[c] in 1993 and 1994

	1993			1994		
Parameter	Low density	High density	*P*	Low density	High density	*P*
Canopy air temperature (C)						
Maximum	27.7	26.0	0.02	29.2	27.1	0.14
Minimum	12.7	12.0	0.04	12.3	12.0	0.43
Average	18.3	17.4	0.03	19.4	18.4	0.05
Range[d]	15.0	14.1	<0.01	16.9	15.1	0.08
Foliage temperature (C)						
Maximum	---[e]	---	---	33.4	32.0	0.38
Minimum	---	---	---	16.2	16.7	0.13
Average	---	---	---	23.0	22.2	0.47
Range	---	---	---	17.1	15.3	0.28
Relative humidity						
Hours with >90%	17.2	17.2	0.97	14.8	17.1	0.04
Minimum (%)	70.9	74.6	0.06	72.7	77.2	0.24
Average (%)	93.3	93.9	0.12	92.7	95.2	0.08
Range (%)	29.1	25.4	0.06	27.4	22.8	0.26

[a] Values presented are least square means. 1993 canopy air temperature and relative humidity data are averages of two blocks measured for 3 and 4 days from 29 August to 4 September. 1994 figures are averages of three blocks measured for 3, 6, and 6 days from 5 August to 21 August. Foliage temperatures were not determined in 1993. 1994 foliage temperature data represent averages of two blocks measured for 5 and 2 days from 5 August to 21 August. Summary statistics were calculated for each 24-h period prior to analysis of variance.

[b] Mean blade density for Fawn measured on 21 July 1993 and on 9 July 1994 were 193 and 137 leaf blades per 95 cm^2, respectively (5).

[c] Mean blade density for Arriba measured on 21 July 1993 and on 9 July 1994 were 384 and 257 leaf blades per 95 cm^2, respectively (5).

[d] Span from daily minimum to daily maximum.

[e] --- = no data.

tivar Arriba. The differential between canopies for minimum and average air temperatures in both years was less than 1°C. The average range was over 1°C higher in the low-density canopies in both years, reflecting greater variation in daily temperatures. In the seeding density experiment, canopy air temperature parameters in low-, medium-, and high-density turfs generally were within 0.3°C of each other and were not statistically significant at the 90% confidence level (Table 2).

Foliage temperature parameters also did not differ appreciably between high- and low-density canopies in both studies. In the cultivar experiment, the two cultivars did not differ in foliage temperature parameters in 1994 (Table 1). Foliage temperature data were not collected in 1993 in the cultivar study. In the seeding density study, there was no statistically significant difference detected among the canopies for most of the canopy temperature parameters over the 2 years (Table 2). The mean range of temperatures in the high-density canopy was 1.1°C greater than in the low-density canopy in 1993, but this was not found in 1994. The differences in all other canopy temperature parameters between high- and low-density canopies were less than 0.8°C.

Some differences between canopies were found in relative humidity and leaf wetness parameters, but were not consistent between years in either study. In both 1993 and 1994, mean relative humidity in the cultivar study was close to 95% and minimum relative humidity exceeded 70% (Table 1). In 1993, there was a lower minimum relative humidity ($P = 0.06$) and a greater range of relative humidity ($P = 0.06$) in the low-density Fawn canopy than in the high-density Arriba canopy, but these differences did not occur in 1994. In 1994, the lower density Fawn had a 2.3-h shorter ($P = 0.04$) duration of relative humidity over 90% and a 2.5% lower average relative humidity ($P = 0.08$) than the higher density Arriba.

Similar trends relating to relative humidity levels were found in the seeding density experiment (Table 2), but there was no significant difference in the number of hours with relative humidity exceeding 90% between low and high density canopies in either year. No significant differences were detected for other relative humidity parameters in 1993. In contrast, the minimum, average, and range of relative humidity were different between low- and high-density canopies of Fawn in 1994. Mean minimum relative humidity levels were 69 and 73% in low- and high-density canopies, respectively. The relative humidity mean daily average was higher in the high-density planting (93%) than in the low-density planting (89%).

Leaf wetness duration in the cultivar study, which was measured only in 1994, was 0.8 h longer ($P = 0.10$) in the higher density canopy Arriba than in the low-density Fawn (Fig. 4A). This was associated with a 1 h later ($P = 0.09$) leaf wetness depletion time in Arriba, but wetness onset times did not differ between cultivars.

In the Fawn seeding density study, no differences in leaf wetness parameters were found in 1993 (Fig. 4B). In 1994, leaf wetness ended over 1-h later ($P = 0.06$) in the high-density canopy than in the low-density canopy in 1994 (Fig. 4C), but leaf wetness onset time and leaf wetness duration did not differ between low- and high-density canopies.

Effect of blade proximity on hyphal growth and disease severity. Proximity of grass blades as determined by plant density (Fig. 2) affected the growth of *R. solani* between leaf blades and the amount of necrosis caused by the fungus under uniform environmental conditions. In the high-seeding-density cups, leaf blades were 3.0 ± 0.2 mm (mean ± standard error, $n = 10$) apart, whereas leaf blades in low-density cups were separated by 6.6 ± 0.3 mm (mean ± standard error, $n = 10$), with distances ranging from 0 to 10 mm. *R. solani* hyphae were observed to bridge distances of up to 8 mm between grass blades in both high- and low-density canopies (Fig. 2B). Interblade hyphal growth occurred more frequently in the high-seeding-density treatment (Fig. 2C) than in the low-density treatment. In the low-seeding-rate treatment, *R. solani* hyphae grew predominantly between grass blades located in close proximity or between blades in direct contact with each other. Fungal hyphae spread through the canopy in the high-seeding-density treatment more rapidly than in the low-density treatment. In one experiment, for example, the focus diameter increased at 9 mm/day in low-density canopies, whereas the focus diameter expanded at 16 mm/day in high-density canopies (Fig. 5). In each of three experiments, the high-seeding-rate treatment sustained over 93% necrosis at 4 days after pathogen inoculation, compared to 58 to 76% necrosis at the low seeding rate (data not shown). Levels of necrosis averaged over the three experiments were 69 and 96% for low and high seeding

Table 2. Summary of temperature and relative humidity conditions[a] measured in 1993 and 1994 in low-, medium-, and high-density canopies[b] of tall fescue (Fawn) as established by different seeding rates

	1993 Canopy density				1994 Canopy density			
Parameter	Low	Medium	High	LSD ($P = 0.10$)	Low	Medium	High	LSD ($P = 0.10$)
Canopy air temperature (C)								
Maximum	30.0	30.3	29.7	NS[c]	23.4	23.6	23.3	0.2
Minimum	17.2	17.3	17.4	0.1	12.6	13.7	11.9	NS
Average	22.5	22.5	22.5	NS	16.4	16.5	16.3	0.1
Range[d]	12.7	13.1	12.3	NS	10.8	9.9	11.4	NS
Foliage temperature (C)								
Maximum	30.1	30.2	30.9	NS	27.0	27.2	26.5	0.4
Minimum	16.5	16.5	16.1	NS	13.9	14.2	13.9	NS
Average	21.9	21.8	21.9	NS	18.7	18.9	18.3	0.3
Range	13.6	13.7	14.9	0.6	13.2	13.0	12.7	NS
Relative humidity								
Hours with >90%	13.6	13.8	14.2	NS	13.3	13.0	14.1	NS
Minimum (%)	65.6	63.4	67.9	NS	68.7	68.3	73.2	0.3
Average (%)	89.5	88.9	90.0	NS	89.3	89.8	92.7	0.6
Range (%)	34.4	36.6	32.1	NS	31.3	31.7	26.8	0.3

[a] Values presented are least square means. 1993 data are averages of four blocks measured 2, 2, 4, and 4 days from 3 August to 13 August 1993. 1994 figures are averages of two blocks measured for 3 days each from 30 August to 4 September 1994. Foliage temperatures were not determined in 1993. 1994 foliage temperature data represent averages of two blocks measured for 5 and 2 days from 5 August to 21 August. Summary statistics were calculated for each 24-h period prior to analysis of variance.

[b] Low-, medium-, and high-density plots were planted with 10, 30, and 50 g of seed per m^2 in 1993. Blade densities in these respective treatments were 162, 265, and 321 blades per 95 cm^2 on 17 August 1993; and 174, 258, and 280 blades per 95 cm^2 on 17 July 1994.

[c] NS = not significant.

[d] Span from daily minimum to daily maximum.

rates, respectively, and were significantly different ($P = 0.02$). When seedlings were incubated for longer periods of time, the pathogen fungus grew onto all leaf blades and 100% necrosis eventually occurred in all experimental units (data not shown).

DISCUSSION

This study showed that the density of a tall fescue canopy can affect microenvironmental conditions. Differences between high- and low-density canopies were detected despite low degrees of freedom in the analysis of variance and high within-treatment variability related in part to daily changes in the weather. To compensate for the variability, we reduced the threshold for significant treatment differences to the 90% confidence level. Ideally, measurements should be made simultaneously in multiple replicate plots, but this was not possible logistically. The influence of canopy density on moisture parameters may have been underestimated in our study because nightly irrigation applied to ensure brown patch disease development may have masked differences in wetness onset times and consequently reduced differences in leaf wetness duration. Furthermore, the differences in leaf wetness we could detect between low- and high-density canopies may have been a function of the height at which we placed the leaf wetness sensors. In a separate study, we found greater variation in leaf wetness duration between canopies of different densities when sensors were placed 5 cm above the soil versus when sensors were placed 2 cm above the soil (unpublished data).

Microenvironmental changes related to canopy density in turn may influence brown patch disease development. While temperature variations were found with differences in canopy density, the temperature differentials were subtle and all foliage temperatures were well within the reported range for optimum growth of *R. solani* isolates that cause brown patch disease (2). Prolonged periods of leaf wetness and relative humidity above 90% found in the high-density Arriba canopy compared to the low-density Fawn canopy may have been of greater biological significance. *R. solani* has been shown to grow on plant surfaces at relative humidities above 90%, with most rapid growth at 100%, i.e., in the presence of leaf wetness (11,14). Yang et al. (9) showed that increases in leaf wetness duration increased the radius of Rhizoctonia aerial blight foci in soybean. Some of the differences in moisture parameters observed in this study were marked compared to temperature parameters, such a 1.2-h increase in leaf wetness duration and a 2.3-h increase in the duration of relative humidity >90% in the comparison of Arriba and Fawn. It is questionable whether a single period of prolonged moisture of these magnitudes would have a significant effect on growth of *R. solani* or on brown patch disease. Extrapolating from data collected at daily intervals in this and other studies (13,14), *R. solani* hyphae grow on foliage at less than 0.7 mm/h at 100% relative humidity and favorable temperatures. It is conceivable, however, that differences in environmental parameters occurring daily could have had a cumulative effect, which contributed to the higher levels of brown patch disease observed in higher density turf (5).

Microclimatic conditions within low- and high-density turfs were not consistent between years. In the seeding density experiment, fewer microenvironmental differences were found between treatments in 1993 than in 1994, whereas the low- and high-density canopies were less distinguishable in 1994 on the basis of blade density and verdure (5). This may have been related to ambient conditions differing considerably between 1993 and 1994 (6,7). Precipitation levels in July and August of 1993 were much higher than in 1994, with twice as much precipitation occurring in July and nearly three times as much in August. Microenvironmental measurements were made in 1993 during a period with abnormally high amounts of precipitation. This could have buffered much of the effect exerted by canopy density on microenvironmental conditions. Much lower levels of solar radiation also were measured in 1993, with longer periods of overcast skies. In addition, minimum air temperatures were higher in 1993 than in 1994, making 1993 an extremely favorable year for brown patch disease.

Despite less pronounced microclimate differences in 1993, differences in brown patch disease were observed between high- and low-density canopies that year (5). The canopy density effect could be attributed to differences in the proximity of leaf blades directly affecting hyphal growth of *R. solani*. In experiments under controlled, uniform conditions, mycelium was observed to grow more readily from blade to blade and thus to spread throughout the canopy at a more rapid rate in seedlings grown at a high population density. This resulted in more rapid expansion of necrosis through the canopy. We observed that tall fescue leaf blades in the field tended to have a more horizontal orientation and to be separated by smaller distances than those of seedlings in the laboratory. Nevertheless, it is conceivable that blade proximity can be a factor contributing to increased disease in high-density turf in the field when environmental conditions favor fungal growth. In extremely wet years such as 1993, when microclimates in all canopies may be equally favorable to disease, the greater opportunity for the fungus to grow between closely situated blades may be the primary mechanism of increased disease in high-density canopies. In a "normal" year, as in 1994, the creation of more favorable microenvironmental conditions within high-density turf may act in concert with the proximity factor to increase brown patch disease severity.

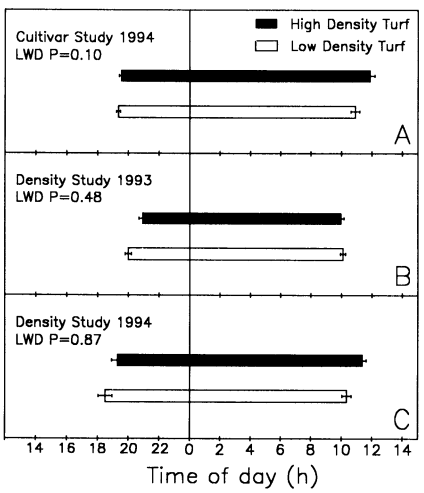

Fig. 4. Comparison of leaf wetness onset and depletion times and leaf wetness durations (LWD) in two studies of tall fescue turfs differing in canopy density. **(A)** Conditions in high- and low-density cultivars (Arriba and Fawn) in 1994. Data are means of measurement made in two blocks for 5 days each. **(B)** Conditions determined in 1993 in high- and low-density turfs created by planting tall fescue Fawn at two seeding rates. Data are means of measurements collected over 1 to 2 days in each of four blocks. **(C)** Conditions determined in 1994 in the Fawn seeding rate study. Data are means of measurements made in two blocks for 3 days each. Error bars denote standard error.

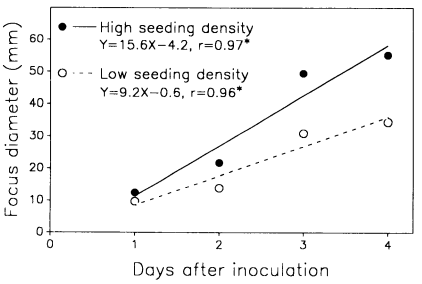

Fig. 5. Spread of *Rhizoctonia solani* AG1-IA hyphae through low- and high-density canopies of tall fescue Fawn seedlings grown in cups and placed under constant high humidity. Two focus diameters were measured per cup and data are means of 11 replicate cups. * denotes $P \leq 0.05$.

ACKNOWLEDGMENTS

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