Quantifying Alfalfa Yield Losses Caused by Foliar Diseases in Iowa, Ohio, Wisconsin, and Vermont

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ABSTRACT

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Although foliar diseases of alfalfa occur throughout the United States wherever alfalfa is grown, little work has been done to quantify yield losses caused by foliar pathogens since the late 1980s. To quantify the yield losses caused by foliar diseases of alfalfa, field experiments were performed in Iowa, Ohio, Vermont, and Wisconsin from 1995 to 1998. Different fungicides and fungicide application frequencies were used to obtain different levels of foliar disease in alfalfa. Visual disease and remote sensing assessments were performed weekly to determine the relationships between disease assessments and alfalfa yield. Visual disease assessments of percentage of defoliation, disease incidence, and disease severity were performed weekly, approximately five to six times during each alfalfa growth cycle. Remote sensing assessments also were obtained weekly by measuring the percentage of sunlight reflected from alfalfa canopies using handheld, multispectral radiometers. Yield loss estimates were calculated as the yield difference between the fungicide treatment with the highest yield and the nonfungicide control, divided by the yield obtained from the highest yielding fungicide treatment $\times 100$. Over the 4-year period, significant alfalfa yield losses ($P \leq 0.05$) occurred on 22 of the 48 harvest dates for the four states. The average significant yield loss for the 22 harvests was 19.3%. Both visual and percentage of reflectance assessments were used as independent variables in linear regression models to quantify the relationships between assessments and alfalfa yield. From 1995 to 1998, visual disease assessments were performed for a total of 209 dates and remote sensing assessments were performed on 198 dates from the four states. Yield models were developed for each of these assessment dates. There were 26/209, 26/209, and 17/209 significant yield models based on percentage of defoliation, disease incidence, and disease severity, respectively. Most of the significant models were for disease assessments performed on or within 1 or 2 weeks of the date of alfalfa harvest. When the significant models were averaged, percentage of defoliation, disease incidence, and disease severity explained 51, 55, and 52% of the variation in alfalfa yield, respectively. There were a total of 68/198 significant alfalfa yield models based on remote sensing assessments, and the significant models (averaged) explained 62% of the variation in alfalfa yield. Alfalfa foliar diseases continue to have a significant negative impact on alfalfa yields in the United States and remote sensing appears to offer a better means to quantify the impact of foliar diseases on alfalfa yield compared with visual assessment methods.

Additional keywords: crop loss modeling, disease assessment, remote sensing

Alfalfa (*Medicago sativa* L.) is the most important forage crop grown worldwide (16). Foliar diseases, such as spring black stem and leaf spot (*Phoma medicaginis* Malbr. & Roum. in Roum. var. *medicaginis*

Boerema; 11,30,31), summer black stem and leaf spot (*Cercospora medicaginis* Ellis & Everh.), common leaf spot (*Pseudopeziza medicaginis* (Lib.) Sacc.), Leptosphaerulina leaf spot (*Leptosphaerulina briosiana* (Pollacci) J. H. Graham & Luttrell), Stemphylium leaf spot (*Stemphylium* spp.), and other foliar pathogens, can cause severe yield losses and lower forage quality (10,11,30–32,34,35). Although some alfalfa cultivars may possess low-to-moderate levels of resistance to individual foliar pathogens, alfalfa cultivars with high levels of resistance to multiple foliar pathogens are not currently available (6,32). In lieu of the lack of effective resistant cultivars to most foliar pathogens, early harvest (cutting) is often recommended to minimize losses caused by se-

vere leaf loss (32). Foliar fungicides are recommended when disease is severe, but only cupric hydroxide is currently registered for use on alfalfa, and this fungicide provides only 30 to 60% disease control (1,2,17,19,20,33).

Disease assessment is the process of quantitatively measuring disease intensity in a host population (5,25,27–29). Two general approaches can be employed to assess disease intensity in a plant population. The first involves a subjective visual disease assessment and the second involves an objective method of measuring reflected sunlight (22,24). Traditionally, visual disease assessment has been the approach most often employed by plant pathologists. This method relies upon subjective evaluation of disease intensity (such as disease incidence, disease severity, and percentage of defoliation) in a host population. Remote sensing has not been employed to assess the impact of foliar diseases on the health and productivity of alfalfa.

Remote sensing is an alternative method to assess disease. Remote sensing is defined as the acquisition of measurements from a sampling unit (alfalfa canopy) without physical contact between the measuring device and the sampling unit (22,24,25). A major advantage of remote sensing is that plant canopies (sampling units) can be objectively and repeatedly analyzed, both nondestructively and noninvasively (22,24). Plants may respond to disease stress in a number of ways, including leaf curling, stunting, wilting, defoliation, and chlorosis or necrosis of photosynthetic plant parts (25). Although many of these responses are difficult to quantify visually with acceptable levels of accuracy and speed, these same plant responses also affect the amount and quality of electromagnetic radiation reflected from plant canopies (22,24,25). Handheld multispectral radiometers are one of the most common types of remote sensing instruments being used in plant pathology to assess the amount of disease injury in crops (22,24).

Foliar diseases result in visible symptoms that can reduce the percentage of sunlight reflected from alfalfa canopies (25); therefore, we hypothesized that foliar diseases assessed visually and by remote sensing would both have significant relationships with alfalfa yield. The objectives

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of this study were to (i) determine the frequency of yield losses in alfalfa caused by foliar diseases in Iowa, Ohio, Vermont, and Wisconsin; (ii) quantify the relationships between visual disease and remote sensing assessments with alfalfa yield; and (iii) compare visual and remote sensing assessment methods to predict alfalfa yield reductions.

MATERIALS AND METHODS

Alfalfa plots were established in 1995 and 1996 using cv. ICI 630 in Iowa, Ohio, and Vermont, and cv. Persist in Wisconsin. These two alfalfa cultivars are highly resistant to bacterial wilt, Fusarium wilt, and Phytophthora root rot, and both are resistant to Verticillium wilt (6). Persist is moderately resistant to Aphanomyces root rot and anthracnose (*Colletotrichum trifolii* Bain & Essary), whereas ICI 630 is resistant to both of these diseases. Although both cultivars are resistant to most races of *C. trifolii*, these cultivars are not reported to be resistant to any other foliar diseases of alfalfa (6).

Foliar disease epidemics were allowed to develop naturally in this study, except that four fungicides that varied in efficacy

(mancozeb, propiconazole, cupric hydroxide, and chlorothalonil) were used to differentially control foliar diseases of alfalfa (1,2,11,13,17,19,20,31,33). To obtain a wider range of foliar disease levels, different application frequencies (once or twice per growth cycle) also were employed (Table 1). Of the four fungicides used in this study, only cupric hydroxide is currently registered for use on alfalfa and this fungicide is reported to be the least effective (of the four) in controlling foliar pathogens of alfalfa (1,2,13,17,19,20,33). An additional biological control treatment (CGA-245704; Novartis Inc., Greensboro, NC) was used in Iowa. At each location and for each growth cycle, the first fungicide was applied when alfalfa canopies were approximately 15 cm high. The second fungicide application was applied 10 to 14 days following the first application. Fungicides were applied in 718 liters of water (equivalent) per hectare using a CO₂-pressurized sprayer at 40 psi (276 kPa). The experimental design was a randomized complete block with four replications. Each plot was 7.5 m long and 1.8 m wide, with 1.2-m borders surrounding each plot. Alfalfa yields were determined by harvesting the center 0.91- to 1.22-m strip of each plot when alfalfa reached 10% bloom. Sickle bar mowers were used in Iowa and Wisconsin, whereas forage flail harvesters were used in Ohio and Vermont. Subsamples of forage were dried in air-forced ovens at 60°C to determine dry matter content. Plot fresh weight then was converted to dry matter yield. There were two harvests in the seeding year and three harvests in the subsequent years, except in Ohio, where there were four harvests following the seeding year. Percentage of yield loss was calculated as the difference between the highest yield achieved using fungicide and the yield from the control treatment, divided by the highest yield achieved $\times 100$ (28). The percentage of yield loss (kg/ha) for each location, date, and harvest (growth cycle) among fungicide treatments were tested for significance

($P \leq 0.05$) compared with controls using analysis of variance and orthogonal contrasts (SAS Institute, Cary, NC).

Visual disease assessments were conducted approximately once a week during each growth cycle (13,15). Sampling for visual disease assessments began when alfalfa canopies were 15 cm high (just prior to the application of fungicides). Ten alfalfa stems were arbitrarily sampled from each plot by cutting the stems at the soil line for each disease assessment date (1–3,13,31). Percentage of defoliation was determined by counting the number of primary leaves (the leaf that develops from each node on a stem) missing from each node, divided by the total number of nodes $\times 100$. Disease incidence was determined by counting the number of symptomatic primary leaves, divided by the total number of primary leaves assessed for each alfalfa stem. Disease severity was determined by estimating the percentage of area covered by lesions due to foliar pathogens for each primary leaf present on each stem.

The percentage of sunlight reflected from alfalfa canopies was measured at each location using a handheld, multispectral radiometer (CROPSCAN Inc., Rochester, MN). Both the incident radiation and the radiation reflected from alfalfa canopies were recorded simultaneously in eight narrow (50-nm) wavelength bands with midpoint values at 460, 510, 560, 610, 660, 710, 760, and 810 nm. All assessments were obtained using a sensor height of 2 m above the ground (14). The area of alfalfa canopy measured for each remote sensing assessment was a 1-m diameter circle (equal to one-half the sensor height).

Single-point yield models were constructed using linear regression for each assessment date by regressing visual disease and remote sensing assessments (obtained each week) against alfalfa yield using SAS (SAS Institute; 9,26). The goodness-of-fit for models was determined by evaluating the *F* test ($P \leq 0.05$) for each model, as well as the coefficient of determination (R^2), the standard error of

Table 1. Fungicide treatments applied on alfalfa to generate different levels of disease for experiments conducted in Iowa, Ohio, Vermont, and Wisconsin between 1995 and 1998

Fungicide	Application frequency	Active ingredient/ha
Chlorothalonil	Once	2.04 liters
Chlorothalonil	Twice	2.04 liters
Cupric hydroxide	Once	1.97 kg
Cupric hydroxide	Twice	1.97 kg
Mancozeb	Once	1.97 kg
Mancozeb	Twice	1.97 kg
Propiconazole	Once	0.25 liters
Propiconazole	Twice	0.25 liters
CGA-245704 ^a	Twice	0.035 kg
Nonfungicide control	None	...

^a Biological control treatment that was applied only in Iowa.

Table 2. Predominant foliar pathogens present during each alfalfa growth cycle in Iowa, Ohio, Vermont, and Wisconsin in 1995 to 1998

State	Alfalfa growth cycle ^a			
	First	Second	Third	Fourth
Iowa	<i>Phoma medicaginis</i> var. <i>medicaginis</i> , <i>Pseudopeziza medicaginis</i> , <i>Xanthomonas campestris</i> pv. <i>alfalfae</i>	<i>Pseudopeziza medicaginis</i> , <i>Cercospora medicaginis</i>	<i>Leptosphaerulina briosiana</i> , <i>Phoma medicaginis</i> var. <i>medicaginis</i>	...
Ohio	<i>Phoma medicaginis</i> var. <i>medicaginis</i> , <i>Leptosphaerulina briosiana</i>	<i>Leptosphaerulina briosiana</i> , <i>Phoma medicaginis</i> var. <i>medicaginis</i>	<i>Leptosphaerulina briosiana</i> , <i>Phoma medicaginis</i> var. <i>medicaginis</i>	<i>Leptosphaerulina briosiana</i> , <i>Phoma medicaginis</i> var. <i>medicaginis</i>
Vermont	<i>Phoma medicaginis</i> var. <i>medicaginis</i>	<i>Phoma medicaginis</i> var. <i>medicaginis</i> , <i>Pseudopeziza medicaginis</i> , <i>Leptosphaerulina briosiana</i> , <i>Stemphylium</i> spp.	<i>Phoma medicaginis</i> var. <i>medicaginis</i> , <i>Pseudopeziza medicaginis</i> , <i>Leptosphaerulina briosiana</i> , <i>Stemphylium</i> spp.	...
Wisconsin	<i>Phoma medicaginis</i> var. <i>medicaginis</i> , <i>Pseudopeziza medicaginis</i> , <i>Peronospora trifoliorum</i>	<i>Pseudopeziza medicaginis</i> , <i>Cercospora medicaginis</i> , <i>Leptosphaerulina briosiana</i>	<i>Phoma medicaginis</i> var. <i>medicaginis</i> , <i>Pseudopeziza medicaginis</i>	...

^a There were typically three growth cycles for all states except Ohio, in which there were four growth cycles per season.

the estimate for y (SE E_y), the coefficient of variation (CV), and a visual inspection of the residual plots (26). The R^2 indicates the proportion of the variation in alfalfa yield (Y) that is explained by an independent variable (visual or remote sensing assessments). The higher the R^2 , the more variation in alfalfa yield that is explained by the independent variable. The SE E_y is the square root of the unexplained variation of alfalfa yield, and it provides a measure of the error for predicted alfalfa yield. The lower the SE E_y value, the more precise the model is to predict alfalfa yield. The CV, defined as the square root of mean square error (SE E_y), divided by grand mean of Y (alfalfa yield), was also used to test the precision of models. The higher the CV value, the lower the precision of the model (method) to predict yield (27).

RESULTS

Predominant foliar pathogens in the four states. The predominant foliar pathogens present during each growth cycle for each state are shown in Table 2. The predominant foliar pathogens among the four states were similar, except that *Xanthomonas campestris* pv. *alfalfae* (Riker et al.) Dye occurred in Iowa, *Stemphylium* spp. occurred in Vermont, and *Peronospora trifoliorum* de Bary occurred in Wisconsin.

Fungicide efficacy. Chlorothalonil applied once or twice per alfalfa growth cycle provided the best disease control (based on assessments of percentage of defoliation) for 22 of the 48 alfalfa growth cycles, whereas mancozeb applied once or twice provided the best disease control for 11 out of the 48 total growth cycles (Table 3). Propiconazole (applied once or twice) provided the best control for 9 of the 48 alfalfa growth cycles, whereas cupric hydroxide (applied once or twice) provided the best control for 6 alfalfa growth cycles (Table 3). Overall, a single application of any fungicide provided the best control for 15 of the 48 growth cycles, whereas two applications per growth cycle provided the best control for 33 of the 48 alfalfa growth cycles.

Yield loss frequencies. Alfalfa foliar diseases caused significant ($P \leq 0.05$) yield losses in all four states from 1995 to 1998 (Table 4). Alfalfa foliar diseases caused significant yield losses for 22 out of 48 alfalfa harvests (growth cycles) that were conducted over the four states and 4 years. For the two locations (Ames and Nashua) in Iowa, yield losses ranged from 7.9 to 33.9%, with an average of 16.5%. Of the 16 harvests conducted at Iowa, 10 had significant yield losses when compared with the control plots. For Ohio, yield losses ranged from 3.0 to 23.0%, with an average of 9.6%, and 3 out of the 10 harvests had significant yield losses. For Vermont, yield losses ranged from 0.4 to 23.7%, with an average of 15.0%, and 8 out of the 14 harvests had significant yield

losses. For Wisconsin, 1 out of the 8 harvests had a significant yield loss (14.7%).

Although 26 of the 48 alfalfa harvests did not experience statistically significant yield losses, reductions in yield did occur in all 48 growth cycles. Among the 48 harvests in the four states from 1995 to 1998, 5 harvests had yield losses less than 5%, 17 harvests had yield losses between 5 and 10%, 8 harvests had yield losses between 10 and 15%, 7 harvests had yield losses between 15 and 20%, 9 harvests had yield losses between 20 to 25%, and 2 harvests had yield losses exceeding 25% (Fig. 1). No yield losses less than 5% occurred in Iowa during the period from 1995 to 1998 and all yield losses in Wisconsin were less than 15%.

Yield models based on percentage of defoliation. There were significant linear relationships between percentage of defoliation and alfalfa yield for 26 of the 209 models (12.4%) for the four states over 4 years (Table 5). Most of the nonsignificant models were for disease and remote sensing assessment that were performed 2 or more weeks prior to alfalfa harvests when disease levels were still quite low (13). The R^2 values for the significant models ranged from 0.41 to 0.66, which indicates that percentage of defoliation explained up to 66% of the variation in alfalfa yield. The slopes for these significant models ranged from -0.0246 to -0.1660×10^3 kg/ha, which indicates that alfalfa yield decreased 24.6 to 166 kg/ha with each 1% increase in

Table 3. Number of alfalfa growth cycles in which a specific fungicide treatment provided the best control of alfalfa foliar pathogens in Iowa, Ohio, Vermont, and Wisconsin in 1995 to 1998^a

Treatment ^b	State				Total
	Iowa	Ohio	Vermont	Wisconsin	
Chlorothalonil (1)	2	1	1	0	4
Chlorothalonil (2)	9	3	5	1	18
Cupric Hydroxide (1)	0	1	1	1	3
Cupric Hydroxide (2)	1	0	2	0	3
Mancozeb (1)	1	1	2	0	4
Mancozeb (2)	1	3	0	3	7
Propiconazole (1)	2	1	0	1	4
Propiconazole (2)	0	0	3	2	5
CGA-245704 (2) ^c	0	...	...	...	0
Nonfungicide control	0	0	0	0	0
Total cycles ^d	16	10	14	8	48

^a Best control is based upon assessments for percentage of defoliation.

^b The number in parentheses following the treatment indicates the number of applications per alfalfa growth cycle.

^c This biological control treatment was used only in Iowa.

^d Total number of alfalfa growth cycles for which fungicide treatments were evaluated in each state in 1995 to 1998.

Table 4. Alfalfa yield loss (%) caused by foliar diseases in Iowa, Ohio, Vermont, and Wisconsin from 1995 to 1998^a

State, location	Year	Harvest ^b			
		1	2	3	4
Iowa					
Ames	1995	28.3*	33.9*	...	...
	1996	19.5*	8.8	11.7*	...
	1997	21.9*	16.6	10.2*	...
Nashua	1996	8.6	23.1*	...	...
	1997	7.9	8.3	19.3*	...
	1998	15.7*	16.5*	13.9	...
Ohio					
Columbus	1995	3.9	9.0*	...	...
	1996	23.0*	5.5	3.0	13.3
	1997	9.3	14.3*	9.2	5.6
Vermont					
Swift	1995	17.2	23.7*	...	...
	1996	18.4*	12.8*	22.1*	...
	1997	22.9*	20.1*	23.4*	...
Spear	1996	5.7	20.6*	4.2	...
	1997	9.5	0.4	8.6	...
Wisconsin					
Arlington	1995	5.3	6.4	...	...
	1996	0.0	14.7*	7.0	...
	1997	8.7	6.2	13.3	...

^a Percentage of yield loss was calculated as the difference between the highest yield achieved using fungicide and the yield from the control treatment, divided by the highest yield achieved $\times 100$.

^b Percentage of yield loss followed by * is significantly different from the control at $P \leq 0.05$ level using analysis of variance and orthogonal contrasts.

percentage of defoliation. The SEEy ranged from 0.11 to 0.34×10^3 kg/ha, which indicates the standard error using percentage of defoliation to predict alfalfa yield would be ± 110 to 340 kg/ha. CV values for those models ranged from 2.75 to 12.23.

Yield models based on disease incidence. There were 26 significant yield models based on disease incidence among the total 209 models (12.4%) for the four states over the 4 years (Table 6). Again, most of the significant models were for dates when disease incidence was assessed

close to the time of harvest. The R^2 values for those 26 significant models ranged from 0.40 to 0.72, which indicates that disease incidence explained up to 72% of the variation in alfalfa yield. The slopes for these significant models ranged from -0.0082 to -0.1470×10^3 kg/ha, which indicates that alfalfa yield decreased 8.2 to 147 kg/ha with each 1% increase in disease incidence. The SEEy ranged from 0.08 to 0.28×10^3 kg/ha, which indicates the standard error using disease incidence to predict alfalfa yield would be ± 80 to 280 kg/ha. CV values for these significant models ranged from 1.64 to 12.08.

Yield models based on disease severity. There were 17 significant yield models based on percentage of disease severity among the total 209 models (8.1%) developed for the four states over the 4 years (Table 7). The R^2 values for these 17 significant models ranged from 0.39 to 0.76, which indicates that disease severity explained up to 76% of the variation in alfalfa yield. The slopes for these significant models ranged from -0.0085 to -0.3000×10^3 kg/ha, which indicates that alfalfa yield decreased 8.5 to 300 kg/ha with each 1% increase in disease severity. The SEEy ranged from 0.05 to 0.35×10^3 kg/ha, which indicates that the standard error using disease severity to predict alfalfa yield would be ± 50 to 350 kg/ha. CV

Fig. 1. Frequency of percentage of alfalfa yield lost due to foliar diseases for the 48 harvests in Iowa, Ohio, Vermont, and Wisconsin from 1995 to 1998.

Table 5. Coefficients of determination (R^2), intercepts, slopes, standard errors of the estimate for y (SEEy), and coefficients of variation (CV) for significant ($P \leq 0.05$) alfalfa yield models based on percentage of defoliation for Iowa, Ohio, Vermont, and Wisconsin from 1995 to 1998^a

State, location, year	Harvest	DOY ^b	R^2	Intercept	Slope	SEEy	CV
Iowa, Ames							
1995	1	199	0.47	2.69	-0.0797	0.18	11.86
	1	209	0.44	2.26	-0.0318	0.18	12.23
	2	251	0.52	2.71	-0.0252	0.15	9.55
1996	1	149	0.48	7.04	-0.0379	0.23	4.15
	1	155	0.48	7.34	-0.0361	0.23	4.13
	1	162	0.50	7.91	-0.0472	0.22	4.06
1997	3	247	0.50	7.55	-0.0595	0.18	3.51
	1	147	0.45	9.42	-0.1360	0.34	6.03
	1	153	0.49	10.99	-0.1660	0.32	5.78
	1	160	0.60	10.55	-0.1410	0.29	5.11
	3	230	0.48	5.06	-0.0361	0.12	2.75
Iowa, Nashua							
1996	1	178	0.55	3.72	-0.1150	0.21	7.10
	1	193	0.46	4.65	-0.0836	0.23	7.73
	2	227	0.52	3.31	-0.0426	0.18	6.62
	2	234	0.50	3.20	-0.0246	0.18	6.76
1997	2	205	0.66	5.87	-0.0467	0.13	3.11
	3	243	0.59	5.31	-0.0447	0.21	5.48
	1	141	0.41	10.06	-0.0943	0.23	3.60
Ohio, Columbus							
1995	1	186	0.50	4.66	-0.0478	0.15	3.36
1996	1	109	0.65	5.75	-0.1030	0.24	5.20
1996	1	144	0.44	8.65	-0.1030	0.30	6.62
Vermont, Swift							
1996	3	232	0.64	4.31	-0.0944	0.16	5.04
1997	3	230	0.57	2.48	-0.1100	0.11	7.23
Vermont, Spear							
1996	3	232	0.61	5.63	-0.1230	0.27	6.70
1997	2	189	0.43	1.57	-0.0768	0.19	6.31
Wisconsin, Arlington							
1997	1	161	0.41	5.82	-0.0432	0.13	3.38

^a Percentage of defoliation was determined by counting the number of primary leaves (the leaf that develops from each node on a stem) missing from each node, divided by the total number of nodes $\times 100$.

^b DOY = day of year when disease defoliation assessment was conducted.

values for these significant models ranged from 1.79 to 8.11.

Yield models based on remote sensing assessments. Percentage of reflectance in the near-infrared wavelength bands (760

and 810 nm) had stronger linear relationships with alfalfa yield (higher R^2 values) compared with the percentage of sunlight that was reflected between 460 and 710 nm (*data not shown*). Although models based

on percentage of reflectance at 810 and 760 nm had a similar relationship with alfalfa yield, the 810-nm band had lower SEEy values, slightly higher R^2 values, and residuals that were more randomly distrib-

Table 6. Coefficients of determination (R^2), intercepts, slopes, standard errors of the estimate for y (SEEy), and coefficients of variation (CV) for significant ($P \leq 0.05$) alfalfa yield models based on disease incidence for Iowa, Ohio, Vermont, and Wisconsin from 1995 to 1998^a

State, location, year	Harvest	DOY ^b	R^2	Intercept	Slope	SEEy	CV
Iowa, Ames							
1995	1	185	0.46	7.56	-0.0706	0.18	12.08
1996	1	121	0.62	7.55	-0.0734	0.19	3.48
		127	0.55	7.50	-0.0221	0.21	3.84
	2	190	0.47	5.47	-0.0123	0.10	2.25
		197	0.72	5.46	-0.0140	0.08	1.64
		201	0.55	5.26	-0.0083	0.10	2.06
	3	233	0.59	7.16	-0.0340	0.17	3.23
		240	0.40	7.00	-0.0297	0.20	3.87
		247	0.43	9.83	-0.0619	0.20	3.79
1997	2	181	0.64	18.46	-0.1470	0.19	3.88
	3	225	0.59	9.72	-0.0614	0.11	2.46
Iowa, Nashua							
1996	2	213	0.72	3.50	-0.0266	0.14	5.08
		220	0.64	3.85	-0.0207	0.15	5.65
		227	0.44	3.87	-0.0210	0.19	7.10
1998	1	134	0.47	9.29	-0.0365	0.22	3.45
	2	189	0.71	15.53	-0.1430	0.15	3.81
	3	232	0.47	9.10	-0.0688	0.18	5.07
Ohio, Columbus							
1996	1	116	0.53	6.95	-0.0393	0.28	6.08
		130	0.57	8.03	-0.0477	0.26	5.79
		137	0.53	7.47	-0.0426	0.28	6.08
		144	0.54	7.41	-0.0371	0.27	6.03
		151	0.62	7.72	-0.0401	0.25	5.49
1997	4	245	0.45	3.40	-0.0082	0.05	1.88
Vermont, Swift							
1996	3	247	0.50	6.76	-0.0420	0.19	5.98
1997	3	230	0.54	8.01	-0.0710	0.12	7.48
Vermont, Spear							
1997	3	182	0.61	8.96	-0.0686	0.15	5.22
Wisconsin, Arlington	No significant models						

^a Disease incidence was determined by counting the number of symptomatic primary leaves, divided by the total number of primary leaves assessed for each alfalfa stem $\times 100$.

^b DOY = day of year when disease incidence assessment was conducted.

Table 7. Coefficients of determination (R^2), intercepts, slopes, standard errors of the estimate for y (SEEy), coefficients of variation (CV) for significant ($P \leq 0.05$) alfalfa yield models based on disease severity for Iowa, Ohio, Vermont, and Wisconsin from 1995 to 1998^a

State, location, year	Harvest	DOY ^b	R^2	Intercept	Slope	SEEy	CV
Iowa, Ames							
1995	1	199	0.76	3.81	-0.1240	0.12	7.97
	2	229	0.66	3.02	-0.1900	0.13	8.11
1996	1	127	0.57	6.51	-0.0842	0.21	3.76
		134	0.65	6.42	-0.0832	0.19	3.41
	2	201	0.50	5.19	-0.1740	0.10	2.18
1997	1	132	0.47	7.69	-0.2700	0.35	6.23
	3	247	0.45	5.13	-0.0648	0.13	2.98
Iowa, Nashua							
1996	2	206	0.39	3.07	-0.3000	0.20	7.43
		213	0.49	3.16	-0.2930	0.18	6.76
1997	2	198	0.50	5.35	-0.1100	0.16	3.77
Ohio, Columbus							
1995	2	219	0.55	3.90	-0.0928	0.12	3.90
1996	1	109	0.45	5.78	-0.0836	0.30	6.57
	1	116	0.45	6.26	-0.0901	0.30	6.59
1997	4	262	0.50	2.89	-0.0085	0.05	1.79
Vermont, Swift							
1995	2	210	0.59	4.92	-0.0811	0.21	6.19
		229	0.42	4.19	-0.0585	0.24	7.36
1996	3	247	0.52	4.21	-0.0806	0.18	5.83
Wisconsin, Arlington	No significant models						

^a Disease severity was determined by estimating the percentage of area covered by lesions due to foliar pathogens for each primary leaf present on each stem.

^b DOY = day of year when disease severity assessment was conducted.

Table 8. Coefficients of determination (R^2), intercepts, slopes, standard errors of the estimate for y (SE E_y), and coefficients of variation (CV) for significant ($P \leq 0.05$) alfalfa yield models based on percentage of reflectance (810 nm) for Iowa, Ohio, Vermont, and Wisconsin from 1995 to 1998^a

State, location, year	Harvest	DOY ^b	R^2	Intercept	Slope	SE E_y	CV
Iowa, Ames	1995	1	0.74	-5.04	0.13	0.13	8.30
		2	0.55	-6.34	0.13	0.15	9.45
		251	0.72	-1.87	0.067	0.12	7.73
	1996	1	0.51	0.44	0.11	0.22	4.01
		134	0.53	2.89	0.059	0.22	3.95
		141	0.55	1.97	0.065	0.21	3.87
		149	0.66	-1.87	0.14	0.18	3.34
		155	0.77	-1.42	0.14	0.15	2.78
		162	0.77	-1.90	0.14	0.15	2.75
		233	0.42	-1.13	0.11	0.20	3.80
	1997	240	0.73	-2.24	0.13	0.13	2.59
		247	0.62	-1.57	0.12	0.16	3.07
		1	0.44	-7.85	0.35	0.32	5.78
		139	0.60	-7.67	0.32	0.28	5.09
		147	0.53	-12.11	0.36	0.31	5.55
		153	0.57	-8.92	0.29	0.30	5.33
		160	0.69	-8.27	0.29	0.25	4.50
		2	0.80	-2.60	0.15	0.14	2.93
		203	0.91	-3.54	0.17	0.09	1.98
		3	0.44	-7.64	0.22	0.13	2.87
		237	0.69	-4.42	0.16	0.10	2.12
		247	0.57	-1.15	0.11	0.11	2.52
Iowa, Nashua	1996	1	0.49	-3.29	0.14	0.22	7.52
		185	0.77	-2.88	0.12	0.15	5.03
		193	0.75	-3.20	0.13	0.15	5.27
		2	0.65	-5.95	0.17	0.15	5.71
		227	0.85	-4.74	0.15	0.10	3.68
	1997	234	0.78	-0.62	0.07	0.12	4.47
		2	0.47	-0.87	0.11	0.16	3.90
		205	0.76	-0.31	0.10	0.11	2.65
		3	0.54	-14.38	0.39	0.23	5.82
		238	0.53	-10.66	0.27	0.23	5.90
	1998	243	0.44	-4.95	0.17	0.24	6.19
		2	0.78	-2.84	0.15	0.13	3.28
		197	0.90	-2.01	0.13	0.10	2.25
		3	0.48	-3.12	0.17	0.18	5.03
		226	0.51	-2.97	0.15	0.17	4.88
		240	0.44	-0.52	0.09	0.18	5.18
		248	0.53	-0.04	0.08	0.17	4.79
Ohio, Columbus	1995	1	0.46	-2.36	0.13	0.15	3.49
		2	0.87	-4.42	0.16	0.07	2.07
		229	0.50	-2.57	0.11	0.13	4.08
		233	0.45	-3.76	0.12	0.14	4.28
		237	0.53	-1.90	0.08	0.13	3.98
	1996	1	0.45	-8.21	0.23	0.30	6.54
		134	0.55	-1.83	0.13	0.27	5.97
		151	0.53	-3.12	0.15	0.27	6.04
		4	0.65	-6.07	0.18	0.09	8.89
		232	0.79	-7.47	0.22	0.07	6.97
		235	0.85	-5.62	0.15	0.06	5.86
		239	0.79	-4.64	0.13	0.07	6.85
		242	0.80	-4.99	0.14	0.07	6.73
		247	0.90	-3.60	0.11	0.05	4.82
		254	0.68	-3.31	0.11	0.09	8.47
	1997	1	0.89	-7.51	0.20	0.07	1.36
		133	0.60	-9.00	0.22	0.12	2.57
		139	0.57	-3.87	0.14	0.13	2.68
		142	0.55	-4.81	0.19	0.19	3.83
		170					

(continued on next page)

^a Percentage of reflectance of sunlight reflected from plant canopies (810 nm) was measured using a hand-held CROPSCAN multispectral radiometer using a 2-m sensor height.

^b DOY = day of year when reflectance data was collected.

uted; therefore, only percentage of reflectance at 810 nm was selected to develop alfalfa yield models.

There were 68 significant yield models based on percentage of reflectance at 810 nm among the total of 198 yield models (34.3%) developed for the four states over

the 4 years, and nearly all models based on assessment performed on the day of harvest or 1 week earlier were significant (Table 8). In Iowa, there were 39 significant models among a total of 91 yield models developed. The R^2 values for these 39 models ranged from 0.42 to 0.91, which

indicates that percentage of reflectance at 810 nm explained up to 91% of the variation in alfalfa yield. The intercepts ranged from -14.38 to 2.89×10^3 kg/ha. The slopes for the 39 significant models ranged from 0.059 to 0.39×10^3 kg/ha, which indicates that alfalfa yield increased 59 to

Table 8. (continued from preceding page)

State, location, year	Harvest	DOY ^b	R ²	Intercept	Slope	SE _{Ey}	CV
Vermont, Swift	1	179	0.61	-2.26	0.09	0.09	13.00
		192	0.53	-4.55	0.17	0.10	14.12
	1996	182	0.59	-3.37	0.18	0.14	3.92
		191	0.75	-8.13	0.24	0.11	3.10
	1997	147	0.53	-7.10	0.25	0.17	4.54
		160	0.50	-1.03	0.10	0.18	4.69
Vermont, Spear	3	245	0.60	-1.57	0.07	0.11	7.02
	1996	182	0.52	-3.56	0.18	0.26	7.05
		191	0.48	-4.03	0.15	0.27	3.39
	3	232	0.45	-4.19	0.15	0.32	7.92
Wisconsin, Arlington	No significant models						

Table 9. Total number of visual disease assessment dates and the total number of significant models based on visual disease assessments in Iowa, Ohio, Vermont, and Wisconsin from 1995 to 1998

State	No. dates ^b	No. of significant models based on ^a		
		Defoliation (%) ^c	Incidence ^d	Severity ^e
Iowa	88	18	17	10
Ohio	43	3	6	4
Vermont	55	4	3	3
Wisconsin	23	1	0	0

^a Regression models were significant when *F* statistics were $P \leq 0.05$.

^b Total number of assessment dates; alfalfa plots were assessed weekly for each alfalfa growth cycle.

^c Percentage of defoliation was determined by counting the number of primary leaves (the leaf that develops from each node on a stem) missing from each node, divided by the total number of nodes $\times 100$.

^d Disease incidence was determined by counting the number of symptomatic primary leaves, divided by the total number of primary leaves assessed for each alfalfa stem $\times 100$.

^e Disease severity was determined by estimating the percentage of area covered by lesions due to foliar pathogens for each primary leaf present on each stem.

390 kg/ha with each 1% increase in percentage of reflectance at 810 nm for different assessment dates. SE_{Ey} ranged from 0.09 to 0.32×10^3 kg/ha, which indicates the standard error using percentage of reflectance to predict alfalfa yield was ± 90 to 320 kg/ha. The CV for the 39 significant models ranged from 1.98 to 9.45.

There were 19 significant models among the 53 models (35.8%) developed in Ohio. The R^2 values for these 19 significant models ranged from 0.45 to 0.90, which indicates that percentage of reflectance at 810 nm explained up to 90% of the variation in alfalfa yield. The intercepts ranged from -9.00 to -1.83×10^3 kg/ha. The slopes ranged from 0.08 to 0.23×10^3 kg/ha, which indicates that alfalfa yield increased 80 to 230 kg/ha with every 1% increase in percentage of reflectance. The SE_{Ey} ranged from 0.05 to 0.30×10^3 kg/ha. The CV ranged from 1.36 to 8.89.

There were 10 significant models among 45 models (22.2%) developed in Vermont. The R^2 values for the 10 significant models ranged from 0.45 to 0.75, which indicates that percentage of reflectance at 810 nm explained up to 75% of the variation in alfalfa yield. The intercepts for these 10 significant models ranged from -8.13 to -1.03×10^3 kg/ha. The slopes ranged from 0.07 to 0.25×10^3 kg/ha, which indicates that alfalfa yield increased 70 to 250 kg/ha with each 1% increase in percentage of reflectance. The SE_{Ey} ranged from 0.09 to

0.32×10^3 kg/ha, and the CV ranged from 3.10 to 14.12. There were no significant models among the nine reflectance-based yield models developed in Wisconsin. There were more significant models based on remote sensing assessments than any of the three visual disease assessment methods.

Comparison of assessment methods.

The total number of significant yield models based upon visual assessment methods in relation to the total number of visual disease assessments performed by each state is shown in Table 9. The total number of significant yield models based upon percentage of reflectance in relation to the total number of remote sensing assessments performed by each state is shown in Table 10. Based on these data, the remote sensing assessment method resulted in more significant regression models to predict alfalfa yields.

DISCUSSION

This research demonstrates that alfalfa foliar diseases had significant negative impacts on alfalfa yield for three of the four states involved in the study. The average yield loss caused by foliar diseases averaged over the 48 harvests, as determined by the difference between the highest yielding fungicide treatment and the nonfungicide-treated control, divided by the highest yielding fungicide treatment, was 13.2%. Significant yield losses oc-

Table 10. Total number of remote sensing assessment dates and the total number of significant models based on percentage of reflectance at 810 nm in Iowa, Ohio, Vermont, and Wisconsin from 1995 to 1998^a

State	Total number of assessment dates ^b	Number of significant models ^c
Iowa	91	39
Ohio	53	19
Vermont	45	10
Wisconsin	9	0

^a Percentage of reflectance of sunlight reflected from plant canopies (810 nm) was measured using a handheld CROPSCAN multispectral radiometer using a 2-m sensor height.

^b Assessments were performed weekly for each alfalfa growth cycle.

^c Regression models were significant when *F*-statistics were $P \leq 0.05$.

curred in 22 out of the 48 harvests and the yield loss for those 22 harvests averaged 19.3%. These losses are a little lower than the results obtained by other researchers in other states (3,4,16,30,32). For example, Campbell and Duthie reported that alfalfa yield losses caused by foliar diseases ranged from 5.3 to 37.2% per cutting in North Carolina (4). In Illinois, yield losses caused by foliar diseases were estimated to be as high as 52% per cutting, with an average loss of 15% each year, which was similar to our results (3). In Iowa, Norton reported that alfalfa yield was reduced 44% annually by foliar diseases (23). Wilcoxson et al. reported that alfalfa yield was reduced 30% annually by foliar diseases in Minnesota (35). In California, Gilchrist et al. reported annual yield losses of 20 to 25% caused by foliar diseases (8). Matheron and Matejka reported that alfalfa yield was increased 7.5 to 13.0% annually in Arizona when alfalfa was treated with the fungicide chlorothalonil to control foliar diseases (19,20). Lengkeek reported that alfalfa yield was increased by 7.4% per cutting when foliar diseases were controlled using fungicide mancozeb in Kansas (17). In Wyoming, Gray et al. reported that spring black stem reduced alfalfa yield in the first cutting by approximately 10% (11). One reason that the estimated losses in the present study are slightly lower than

the earlier reports from other studies is the improved resistance to anthracnose (6,32). Moreover, other studies may have included losses from soilborne pathogens, but the present study dealt with quantifying only losses due to foliar pathogens.

The risk of foliar diseases causing significant yield loss for Iowa and Vermont was much higher than for Ohio and Wisconsin. Moreover, there were fewer significant yield models based on visual disease and remote sensing assessments in Wisconsin than in the other three states. In Wisconsin, few growth cycles had significant yield losses, and the range of yield response data within growth cycles was smaller than the range of yields for other states. Another reason that yield losses were lower in Wisconsin might be due to the fact that a different cultivar (Persist) was used in Wisconsin. It is possible that Persist may have been more resistant to foliar diseases than ICI 630, resulting in lower disease levels and a smaller range of visual disease, remote sensing assessments, and yield data among the different fungicide treatments. Cornell and Berger have reported that the R^2 is greatly affected by the range of the independent variables, and the smaller the range, the lower the coefficient of determination (7).

Although alfalfa breeding programs target specific diseases, a number of alfalfa foliar diseases continue to cause significant yield losses. This is because alfalfa cultivars that are resistant to a broad range of foliar diseases are not currently available (6). Attempts to utilize timely harvests prior to the occurrence of defoliation are often ineffective, as evidenced by the losses that occurred in our study and others (3,4,13,23). Furthermore, no effective fungicides are currently registered for alfalfa foliar diseases (17,19). The fungicide that was least effective in controlling foliar pathogens (cupric hydroxide) in this study is the only fungicide currently registered for use on alfalfa. Although the biological control treatment used in Iowa in this study did not provide effective disease control, alternative management tactics, including the use of effective biological controls, need to be investigated. Disease management tactics available to control alfalfa foliar diseases are presently limited.

Averaged over the 48 harvests, the yield loss for the four states over the 4-year period was 13.2%. It is likely that this estimate is somewhat lower than the actual yield losses caused by alfalfa foliar pathogens because none of the fungicide treatments in this study provided 100% disease control. In this study, visual and remote sensing assessments explained a large proportion of the variation in yield using linear regression, and the unexplained variation in yield was likely due to other biotic pests (such as alfalfa weevil, leaf hoppers, and soilborne pathogens) as well as differences in environmental conditions

that affected the yield potentials of experimental plots.

Assuming that the average yield of one hectare of alfalfa is 8.4 tons/year, and assuming there are approximately 9.7 million ha of alfalfa grown in the United States (13,21), the average alfalfa yield loss is estimated to be approximately 10.76 million tons/year. Furthermore, according to the USDA weekly auction market report, the average alfalfa hay price in Iowa from 1995 to 1998 was \$80/ton. Assuming a similar average price throughout the United States, this makes the economic losses approximately equal to \$860.8 million/year in the United States.

This research confirmed our hypothesis that both visual and remote sensing assessments have significant relationships with yield; however, the remote sensing method predicted alfalfa yields with greater precision than any of the three visual disease assessment methods (disease incidence, disease severity, and percentage of defoliation) used in this study. The visual disease assessment methods used in this research only measure the impact of foliar diseases on alfalfa leaves located on the primary nodes of alfalfa stems. This method may not account for total impact that foliar diseases have on the growth and production of lateral branches and leaves. We observed that alfalfa foliar diseases cause premature defoliation and that, if primary leaves (located at the stem nodes) prematurely defoliate, very few lateral branches will develop from affected nodes. We suggest that sampling protocols in the future include the assessment of the presence or absence of lateral branches. Remote sensing assessments, however, provide information about the impact of foliar diseases on all leaves, including those that develop on lateral branches, because the higher the healthy (green) leaf area index, the higher the reflectance in the 810-nm wavelength band (13,24–26). In our study, remote sensing was superior to the visual disease assessment methods as a means to quantify the degree of the plant stress caused by alfalfa foliar pathogens and, thus, yield models based on remote sensing assessment could predict yield with greater precision. Remote sensing also had other advantages over visual disease assessment methods. Remote sensing is nondestructive and more objective than visual assessment methods. The time needed to conduct visual assessments took more than 15 times longer than remote sensing (1 h compared to 15 h). Remote sensing data were stored as electronic files; thus, potential errors associated with data entry also were avoided.

Overall, remote sensing provided a better means to assess the injury associated with foliar diseases than visual disease assessment methods. There are, however, some important factors that should be considered to obtain accurate remote sensing

assessments. A potential disadvantage of the remote sensing method is that percentage of reflectance may be affected by factors other than disease, such as the amount of incident radiation, sun angle, sensor height, leaf wetness, fungicide residue, and wind (12–15,18). These factors should be considered to ensure the accuracy and precision of remote sensing assessments.

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