Quantifying Economic Losses Associated with Levels of Wheat Streak Mosaic Incidence and Severity in the Texas High Plains

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ABSTRACT

Wheat streak mosaic (WSM), caused by the *Wheat streak mosaic virus* (WSMV), which is transmitted by the wheat curl mite (*Aceria tosichella*), is the most prevalent virus disease of wheat in the Texas High Plains. Infected plants initially exhibit mosaic symptoms, which lead to severe stunting, complete chlorosis and, in the most severe cases, eventually plant death. Wheat plants infected with WSMV have lower forage and grain yields and exhibit reduced water-use efficiency compared to non-infected plants. The disease's impact on water-use efficiency raises an important issue of whether diseased fields should be irrigated as frequently as non-diseased fields. The issue becomes more relevant when energy costs and the dwindling water resources from the Ogallala Aquifer are taken into consideration. This study examined the potential economic losses due to WSM, using data collected from two fields in 2007 and 2009. A hand-held hyperspectral radiometer was used to quantify severity of WSM in multiple 1m² plots along two transects, each stretching from the edges of the fields to their centers. Grain yield declined exponentially ($R^2 = 0.79$, $P < 0.0001$) with increasing disease severity, as measured by reflectance at 555 nm. For economic analysis, grain yield from each plot was used for determining cost adjustments and linked revenues in relation to WSM severity levels, which allowed calculations of

potential profit reduction. The method enables one to compare losses associated with different levels of WSM severity to a baseline with little or no WSMV infection. Results show that losses from the disease are primarily an outcome of reduced revenue due to a decrease in grain yield, and, as expected, losses incurred per unit land area rapidly increase with increasing disease incidence and severity. Furthermore, producers incur additional marginal losses when irrigating fields with WSM because there is little or no return for irrigation inputs, as water-use efficiency of severely diseased wheat is drastically reduced. Results from this study are useful in estimating losses at differing levels of disease incidence and severity and represent the first step in development of an economic threshold for wheat streak mosaic.

Keywords: Economic losses, enterprise budgeting, water-use efficiency, wheat curl mite, wheat streak mosaic, *Wheat streak mosaic virus*

1. Introduction

Wheat streak mosaic (WSM), caused by *Wheat streak mosaic virus* (WSMV), is the most widely prevalent virus disease of wheat in the Texas High Plains (Burrows et al. 2009). The virus is transmitted by wheat curl mites (*Aceria tosichella* Keifer), which are typically blown into wheat fields from nearby grass vegetation or fields with mite-infested volunteer wheat (Christian and Wallis, 1993; Wiese, 1987; Price, 2015). Infected plants exhibit leaf symptoms ranging from mosaic and streaking to complete chlorosis and stunting, resulting in substantial yield loss (Atkinson, 1967, Byamukama. Et al. 2014, Workneh et al. 2009). Disease severity gradients are often observed in affected fields, with the most severe symptoms occurring near the edges (Workneh et al. 2009, 2010) but, in some cases, entire fields can be severely affected. In the Texas High Plains region, planting season generally runs from late August through early December and fields are mostly planted to hard red winter wheat as a dual purpose

40 crop (intended both for grain production and winter forage for cattle grazing). Fields planned for grazing
41 are planted early to maximize forage biomass. However, WSM is usually more severe in early planted
42 fields than in fields planted later in the season, which is mainly attributed to an overlap with green grass
43 vegetation (“green bridge”) harboring viruliferous mites (Bowden et al., 1991; Somsen and Seal, 1970;
44 Price, 2015).

45 Wheat plants infected with WSMV have significantly less root weight, plant biomass, and water-use
46 efficiency than non-infected plants (Price et al. 2010; Workneh et al. 2010). Its impact on water-use
47 efficiency raises an important management issue of whether diseased fields should be irrigated as
48 frequently as non-diseased fields. The issue becomes more relevant when energy costs and dwindling
49 water resources in the region are taken into consideration (Postel 1998). Approximately 1/3 of the
50 wheat production in the region (amounting to one million ha) is irrigated with water from the Ogallala
51 Aquifer (Anonymous, 2006). However, there is a growing concern over the decline of the water level in
52 the Aquifer as withdrawals continue to exceed recharges, resulting in increased energy costs for
53 pumping irrigation water (McGuire, 2006; New, 2006). Growers often question whether it will be cost
54 effective to apply midseason management inputs, such as fertilizer, insect control and irrigation, to fields
55 with WSM, due to the lack of information on economic thresholds for differing levels of disease
56 incidence and severity. A recent study on the effect of WSM showed that irrigated wheat producers
57 incurred greater losses to the disease than dry-land producers and that a blanket application of irrigation
58 water to an infected crop would not alleviate the disease problem but rather contribute to the economic
59 loss (Velandia-Parra, et al., 2010). Knowledge of the economic impact of different levels of WSM
60 incidence and severity is essential for identification of disease thresholds, above which additional inputs
61 become unprofitable. For this reason, the primary objective of this study was to estimate economic
62 losses at different levels of WSM incidence and severity.

2. Materials and Methods

2.1. Field data collection and analysis

Wheat streak mosaic severity assessments were conducted in irrigated wheat fields planted to WSM-susceptible cultivars in 2007 and 2009 in Lamb and Hale counties, respectively, in the Texas Panhandle. In each field, two transects were established, stretching from the outside edge to the center of each field. The 2007 field contained 60 sampling locations per transect at 2.5 m intervals, while the 2009 field had 48 in one and 56 in the other, with 6 m intervals. The length of transects and number of sampling intervals were dependent on the length of the disease severity gradient from the edges of the fields.

At each location, when wheat development was between Feekes scale 8-10.1 (Large, 1954), the severity of wheat streak in a 1 m² area (5 rows) was quantified by taking reflectance measurements at 555nm, using a hand-held hyperspectral radiometer (Fig. 1) (SD 2000, Ocean Optics, Dunedin, FL). Others have used different wavelengths to detect and differentiate healthy from diseased plants (Stilwell et al. 2013), but we found that reflectance measurements taken at 555 nm were strongly correlated with visual WSM severity assessments (Workneh et al. 2009). Normally, green healthy leaf tissue produces lower reflectance values while chlorotic diseased leaves produce higher reflectance values (Workneh et al. 2009, 2010; Stilwell et al. 2013; Fig. 1). In late June of each year, wheat at each location along the transects was harvested from 0.8 m² area and the relationship between WSM severity levels and grain yield was determined using regression analysis.

2.2. Economic analysis.

The economic impact of WSM was analyzed using an enterprise budgeting approach, previously described by Kay and Edwards (1999). This approach determines cost adjustments as well as linked revenues in relation to WSM occurrence, which allows for the calculation of potential profit reduction

(per ha). Net revenue is determined by deducting the total variable costs incurred from the gross revenue, and is expressed as:

$$\Pi_w = p_w * Q_w - TVC(Q_w),$$

where Π_w = wheat profit, p_w = wheat price, Q_w = wheat quantity (grain yield), and $TVC(Q_w)$ = total variable cost of wheat production, including seed, fertilizer, irrigation, operator and hand labor, gas, repair, and maintenance. In this analysis, total cost is exclusive of fixed costs such as land rental, major equipment etc. Because of its negative impact on grain yield and quality, WSM affects gross revenue, which is calculated as a product of price and yield. Gross revenue is also affected by the effect of WSM on water-use efficiency, as there is little or no return for irrigation and associated expenses when the disease is severe and widespread. In this study, reductions in revenues due to WSM were estimated using data from the fields described above to calculate its economic impact.

3. Results and Discussion

For both years, the relationship between grain yield and reflectance values showed similar trends, which could easily be explained by an exponential model. Thus, data from both years were combined and fitted to an exponential model $Y = a*(e^{-bX})$ where Y is predicted yield, a and b are parameters, and X is reflectance value ($R^2 = 0.792$, $P < .0001$, Fig. 2). Linear models are generally easier to interpret and would have been better for use in the economic analysis. However, as easily seen in Fig. 2, fitting a linear model would exclude reflectance values above 0.8 (X-axis), which are a very important part of the data. These values represent severely infected areas corresponding to zero or near zero kg/ha in yield. Overall the exponential model provided a good prediction of the yield based on the disease severity levels. However, as seen from the regression and the residual plot graphs (Figs. 2 and 3, respectively), the model under-predicted the yield at lower disease severity levels (reflectance values between 4 and

6), which represent overlapping regions of healthy and diseased areas. The distribution of the residual plots appeared to be random without a clear trend until yield levels of about 3000 kg/ha (which corresponded to healthy or near healthy areas), suggesting that overall the data were well described by the model except near disease-free areas of the fields, where the impact of the disease on yield was less.

The estimated wheat grain yield of 3,921 kg ha⁻¹, which corresponded to the reflectance value of 4.0 (healthy, green tissue reflectance), was representative of, but slightly lower than, the average wheat grain yield of 4,378 kg ha⁻¹ normally observed across the region (New, 2006). However, as the reflectance values increased, the effect on yield increased substantially and grain yield was reduced by 98% at a reflectance of 10.0 (Table 1). The lower and higher yield limits, which corresponded to reflectance values of approximately 10 and 4.0, equaled 76 kg ha⁻¹ (1.1 bu acre⁻¹) and 3,921 kg ha⁻¹ (58 bu acre⁻¹), respectively. Therefore, the estimated loss in wheat grain yield (Table 1) at reflectance level 5 and 100% incidence across the field was calculated to be 1,891 kg ha⁻¹ (3,921 kg ha⁻¹ minus 2,030 kg ha⁻¹) and grain yield loss at reflectance level 10 was estimated as 3,836 kg ha⁻¹ (3,921 kg ha⁻¹ minus 85 kg ha⁻¹).

3.1. Economic analysis: marginal approach

Enterprise budgets were used to determine marginal loss due to different incidence and severity levels of WSM, as well as to provide a comparison between losses at different irrigation levels. Expenses associated with the various scenarios were based upon enterprise budgeting for continuous production on a dual purpose farm in the Texas High Plains (Amosson, et al. 2013). In the published crop enterprise budget, average yield of a normal irrigated crop in the Texas Panhandle was determined to be 4,378 kg/ha (65 bushels/ac), but for this study we used 3,921 kg/ha (58 bushels/ac) as a baseline yield, to be on the conservative side and because that represented the estimated yield in our healthy,

disease free plots with reflectance values of 4.0. Two main sources of economic loss associated with WSM were determined in this study. First, revenues decreased as a result of a reduction in grain yield, and secondly, costs increased as a result of wasted irrigation, fertilizer, pesticides, labor and energy.

The first step in determining the economic impact of WSM was to analyze its effect on grain yield at different WSM severity levels. In this analysis, we defined a healthy, disease free crop as one with a reflectance level of 4 and a grain yield of 3,921 kg ha⁻¹, and also included an estimation of disease incidence as percentage of the field area affected: 25%, 50%, 75% and 100% (Table 1). When disease incidence increased to 25% of field area, and disease severity was moderately low (reflectance level 5.0), grain yield decreased by 473 kg/ha. As disease severity increased to reflectance level 10 and the area affected increased to 100 percent, the reduction in grain yield increased significantly, up to 3,836 kg/ha. Consequently, the revenue per hectare decreased as a result of increasing disease incidence and severity. When disease severity was high (reflectance level of 10.0) and the entire field was affected, revenue loss per hectare increased to \$1,001, compared to \$492 per hectare loss at reflectance level of 5.0 (Table 2), assuming no loss at a reflectance level of 4.

Total expenses were also calculated for each of the reflectance levels and percentages of the field affected by WSM. It should be noted that the total specified expenses decreased per hectare, with increasing disease incidence and severity. This was a result of the decrease in harvesting costs per hectare due to reductions in grain yields associated with higher levels of WSM severity. Also, returns over direct expenses were calculated for the various combinations of reflectance levels and percentage area infected. As expected, return over direct expenses decreased significantly at higher levels of disease incidence and severity.

3.2. Revenue reduction

Reduction in revenue was determined by implementing the reduction in grain yield as a result of disease. Total Revenue (R_w) can be described as:

$$R_w = P_{wy} * Yield_w,$$

where P_{wy} = represents price of wheat and $Yield_w$ = grain yield (kg/ha).

In this analysis, forage loss and loss in hay due to WSM was not included. However, for the calculation of loss in grazing revenue as a result of the disease, estimations could be done for calculating the change in livestock weight gain from grazing. It could therefore be estimated, that weight gain (kg) would be directly reduced by the same percentage as reductions in forage/biomass, resulting from infection by WSMV. However, for WSM to significantly impact forage production and subsequent cattle weight gain, infections would have to occur very early after planting and environmental conditions would have to be highly conducive for mite reproduction and spread and disease development. For most dual purpose fields, wheat is planted in late August to early September, cattle are placed on the field by November and taken off by March 15 to allow development of the grain crop. Based on this schedule, WSM would not cause significant reductions in forage yield and cattle gain in most years. However, in years when the cattle market is high and farmers decide to graze out their fields, WSM could cause significant losses in amount and quality of forage and cattle gain per hectare.

Finally, calculations for estimating total economic loss (\$/ha), due to WSM were also carried out (Table 3). Total economic loss was calculated as the sum of loss in revenue and production expenses already incurred at each combination of disease incidence and severity, compared to no infection. The total economic loss incurred per hectare increases with increasing disease incidence and severity, and therefore it is important to realize the economic consequences of such an infestation and its associated impact on the producers.

3.3. Additional cost

This cost is a result of the wastage of irrigation labor and energy costs, which is indicative of the disease's ability to reduce the wheat plant's capacity to uptake soil moisture (Price et al. 2010; Workneh et al. 2010). For a single crop and growing season, a reduction in water uptake equates to wasting the irrigation water that was applied to the crop, which in turn leads to additional costs associated with the disease. Additional costs associated with WSM included wastage of irrigation labor and energy costs calculated as:

$$TC = w * IL_b + r_e * IE,$$

where TC= Total cost, w = Wage rate \$/hour, IL_b = Man hour required for irrigation per hectare, r_e = \$/hectare-mm energy cost, IE = Irrigation energy units used for wheat production. In using enterprise budgets (Amosson et al. 2013), the price of irrigation labor and energy must be multiplied by the wasted amounts of irrigation labor and energy due to disease, thereby leading to a total additional cost per hectare for the wheat farmer.

3.4. Total marginal loss due to WSM

An analysis was conducted to determine the effect of WSMV at different severity levels on wheat yield, revenue, expenses and returns, at different irrigation levels and when 25% or 100% of the field area was infected. Total marginal loss (TML) per hectare was calculated using the following formula:

$$TML_{WSM} = R_w - TC,$$

where R_w = total revenue and TC = total cost. Table 4 shows the calculations at irrigation levels of 125 mm, 250 mm, and 375 mm respectively, and an estimation of impact when 25% or 100% of the field was affected. It is interesting to note that even at reflectance level 4, the healthy, disease free baseline, losses were incurred at the two lowest irrigation levels of 125mm and 250mm ha^{-1} . Only at the

198 highest irrigation level of 375mm did the corresponding increase in yield compensate for the added
 199 expense of irrigating the crop and result in a profit of \$79 ha⁻¹. In all irrigation × disease incidence
 200 scenarios, total marginal losses increased with increasing disease severity. However, disease incidence
 201 and irrigation amount significantly affected the total marginal losses at a given disease severity level.
 202 When disease incidence was estimated at 25%, increased irrigation resulted in reduced losses at every
 203 disease severity level. In these scenarios, increased yields associated with increased irrigation of the
 204 healthy part of the field reduced losses. Likewise, when disease incidence was estimated at 100% and
 205 disease severity levels were ≤ 6 , losses decreased with increasing irrigation, but with severity levels ≥ 7
 206 losses increased with increasing irrigation. In these scenarios, increased irrigation, with an anticipated
 207 but unrealized increase in grain yield, could not compensate for the high disease incidence and severity.
 208

209 This study examined potential economic losses associated with WSM severity levels, using data
 210 obtained from growers' fields. Grain yield exponentially declined with increasing disease severity
 211 levels, resulting in corresponding revenue reductions. As expected, the loss in revenue also
 212 corresponded with disease incidence, i.e., the percentage of area affected by the disease. Because the
 213 values presented in Tables 2-4 for losses associated with WSM are based on actual data collected from
 214 the farmer's fields, they are accurate for those specific fields, but the numbers presented for yield
 215 reductions and economic losses should probably not be considered absolute for any diseased field, since
 216 fields are inherently highly variable in yield potential. However, we believe that the estimates presented
 217 for percentage losses (values in parenthesis in Tables 1-3) associated with different levels of disease
 218 incidence and severity are reliable and likely applicable to any irrigated field planted to a WSM-
 219 susceptible cultivar. The caveat being that in this study disease severity ratings were taken only once,
 220 when wheat development was at Feekes scale 8 – 10.1. Finally, for irrigated wheat producers, reduction

221 in water-use efficiency in diseased wheat results in additional losses in revenue because of reduction in
 222 return from irrigation input. Inefficient water use in diseased fields and the significance of disease
 223 incidence and severity on grain yields and total revenue points to the need for site-specific precision
 224 irrigation where irrigation inputs are directed to the healthy parts of the field and away from diseased
 225 areas.

226 The results presented here are based on a two-year field study in which disease ratings were taken at
 227 a single window of time when wheat development was at Feekes scale 8 – 10.1. Losses from WSM are
 228 highly dependent on the time during the growing season when plants become infected and disease
 229 severity reaches a given level (Workneh et al. 2009), and estimates of disease incidence and severity
 230 obtained at different crop developmental stages may have impacted results. Taking readings earlier
 231 would have missed later infections that may have negatively impacted yield, and taking readings at a
 232 later developmental stage, while most likely resulting in a better correlation with final yield, would be
 233 too late to provide information to farmers that could be used in making management decision.

234 WSM incidence and severity levels vary from year to year, depending on location and environmental
 235 factors that affect timing of infection, disease development and spread. This in turn results in variations
 236 in its effect on yield and the corresponding impact on revenue. Therefore, the reflectance values used in
 237 this analysis cannot be considered as absolute and readily applicable to all wheat cultivars. Reflectance
 238 of wheat cultivars, even in the absence of any biotic or abiotic stress, can somewhat differ, based on
 239 crop developmental stage when readings are taken, but would not overlap with the reflectance values of
 240 WSM are quite different signatures from those of healthy plants (especially at 555nm, Fig. 1). The
 241 methods and results reported here provide the basis for future research and management of fields where
 242 WSM is prevalent.

Producers of irrigated wheat incur significant economic and natural resource losses as a result of inefficient water use by wheat infected by WSMV (Price et al. 2010; Velandia-Parra et al. 2010; Workneh et al. 2009, 2010). This highlights the need for additional research on site specific, precision irrigation of wheat. Currently, commercial irrigation systems are available that allow site specific precision application, and because of its prevalence in the Western Great Plains irrigated wheat production region and tendency to develop disease severity gradients across fields, WSM provides a perfect research model. Development of an economic irrigation threshold for diseased wheat and adoption of site specific precision irrigation ultimately will lead to conserved ground water, increased irrigation efficiency and increased crop water use efficiency. However, before this is accomplished, detailed cost/benefit analyses of implementing site specific precision irrigation must be conducted, and a better understanding of the relationship between crop developmental stage at time of initial infection and final yield must be achieved.

3.5. Conclusions

Wheat streak mosaic is a major wheat virus disease in the Southern Great Plains of the US. In addition to reducing yield, the disease negatively affects water-use efficiency because the smaller root systems of affected plants are inefficient in water uptake, leading to the wastage of unutilized irrigation water. Furthermore, because WSM frequently develops disease gradients across fields over time, it is very difficult for farmers to know whether additional crop inputs are warranted. The current study estimated the economic impact of WSM at different levels of disease severity, in conjunction with percentage of the field area affected. The study determined that economic losses arise from direct loss of revenue from reduction in yield plus additional marginal losses from irrigating affected plants, as there is little or no return from irrigation inputs with severely diseased plants. Results from this study represent the first step in developing economic thresholds for the disease. These economic thresholds

will enable producers to estimate losses at different levels of WSM incidence and severity and thereby make more informed management decisions with regard to irrigation and other crop inputs.

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Table 1. Estimated wheat grain yield loss (kg ha^{-1}) at different WSM severity levels in relation to the percentage area affected.

Reflectance ^a	Percentage area affected			
	25	50	75	100
4.0	(Baseline grain yield of $3,921\text{kg ha}^{-1}$ with no loss due to WSM)			
5.0	473 (12 ^b)	945 (24)	1,418 (36)	1,891 (48)
6.0	717 (18)	1,435 (37)	2,152 (55)	2,870 (73)
7.0	844 (22)	1,668 (43)	2,533 (65)	3,377 (86)
8.0	910 (23)	1,820 (46)	2,730 (70)	3,639 (93)
9.0	944 (24)	1,888 (48)	3,832 (72)	3,775 (96)
10.0	961 (25)	1,923 (49)	2,884 (74)	3,836 (98)

^a Wheat streak mosaic severity expressed by reflectance at 555 nm. Reflectance value of 4 = little to no disease symptoms and a value of 10 = extremely severe disease symptoms.

^b Values in parenthesis represent percent yield loss relative the uninfected baseline

Table 2. Estimated loss in revenue (\$ ha⁻¹) at different levels of WSM incidence (% area affected) and severity.

Reflectance ^a	Percentage area affected			
	25	50	75	100
4.0	(Baseline revenue with no loss due to WSM \$1,021 ha ⁻¹) ^b			
5.0	123(12) ^c	246 (24)	369 (36)	492 (48)
6.0	187 (18)	373 (37)	560 (55)	747 (73)
7.0	220 (22)	439 (43)	659 (65)	879 (86)
8.0	237 (23)	474 (46)	710 (70)	947 (93)
9.0	246 (24)	491(48)	737 (72)	983 (96)
10.0	250 (24)	501(49)	751 (74)	1,001 (98)

^a Wheat streak mosaic severity expressed by reflectance at 555 nm. Reflectance value of 4 = little to no disease symptoms and a value of 10 = extremely severe disease symptoms.

^b Price of wheat, 26 cents kg⁻¹ (\$7.12 bushel⁻¹) used in analysis was taken from the enterprise budget (Amosson, et al., 2013) and represents a three year average.

^c Values in parenthesis represent percent revenue loss relative to the uninfected baseline.

Table 3. Estimated total economic loss (\$ ha⁻¹)^a at different WSM incidence and severity levels (% area affected).

Reflectance ^b	Percentage area affected			
	25	50	75	100
4.0	(Baseline with no economic loss due to WSM)			
5.0	237 (12) ^c	473 (24)	710 (36)	946 (48)
6.0	359 (18)	718 (37)	1,077 (55)	1,436 (73)
7.0	423 (22)	845 (43)	1,268 (65)	1,690 (86)
8.0	455 (23)	911 (46)	1,366 (70)	1,822 (93)
9.0	472 (24)	945 (48)	1,417 (72)	1,890 (96)
10.0	481 (25)	963 (49)	1,444 (74)	1,925 (98)

^a Total economic loss includes losses in revenue due to WSM and also loss of variable costs such as fertilizer, irrigation, etc.

^b Wheat streak mosaic severity expressed by reflectance at 555 nm. Reflectance value of 4 = little to no disease symptoms and a value of 10 = extremely severe disease symptoms.

^c Values in parenthesis represent percent economic loss relative to the uninfected baseline

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Table 4. Effect of different irrigation levels (mm/ha) and WSM severity on net return or loss (\$ ha⁻¹) when 25% or 100% of the field area is affected with WSM.

Reflectance ^a	Irrigation levels in mm/ha					
	125		250		375	
	25%	100%	25%	100 %	25%	100%
4.0 (Baseline, no loss to WSM)	(284)	-	(103)	-	79	-
5.0	(353)	(560)	(198)	(485)	(44)	(411)
6.0	(387)	(703)	(246)	(685)	(105)	(666)
7.0	(410)	(778)	(278)	(788)	(146)	(799)
8.0	(416)	(818)	(286)	(844)	(156)	(871)
9.0	(422)	(835)	(294)	(868)	(166)	(901)
10.0	(428)	(847)	(302)	(884)	(177)	(922)

^a Wheat streak mosaic severity expressed by reflectance at 555 nm. Reflectance value of 4 = little to no disease symptoms and a value of 10 = extremely severe disease symptoms.

^b Values in parenthesis are negative and represent total marginal loss ($TML_{WSM} = R_w - TC$ where TML_{WSM} = total marginal loss, R_w = total revenue, and TC = total cost).

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Fig.1. Reflectance values of healthy and symptomatic wheat at various wavelengths for one of the fields used in this article

Fig. 2. Relationships between wheat streak mosaic severity, as expressed by reflectance values, and wheat grain yield

Fig. 3. Residual plots of predicted grain yield based on different wheat streak mosaic severity levels as expressed by reflectance values

409 Fig. 1.

Fig. 2.

419 Fig. 3
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