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Planting Date and Variety Selection for Management of Viruses Transmitted by the Wheat Curl Mite (Acari: Eriophyidae)

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Abstract

Wheat is an important food grain worldwide, and it is the primary dryland crop in the western Great Plains. A complex of three viruses (Wheat streak mosaic, Wheat mosaic, and Triticum mosaic viruses) is a common cause of loss in winter wheat production in the Great Plains. All these viruses are transmitted by the wheat curl mite (*Aceria tosichella* Keifer). Once these viruses are established, there are no curative actions; therefore, prevention is the key to successful management. A study was designed to evaluate preventative management tactics (planting date, resistant varieties) for reducing the impact from this virus complex. The main plot treatments were three planting dates, and split-plot treatments were three wheat varieties. Varieties were planted at three different times during the fall to simulate early, recommended, and late planting dates. The varieties evaluated in this study were Mace (virus resistant), Millennium (mild tolerance), and Tomahawk (susceptible). Measurements of virus symptomology and yield were used to determine virus impact. Results consistently showed that the resistant Mace yielded more than Millennium or Tomahawk under virus pressure. In some years, delayed planting improved the yields for all varieties, regardless of their background; however, under the most severe virus pressure the combination of both management strategies was not sufficient to provide practical control of this complex. These results illustrate the importance of using a combination of management tactics for this complex, but also reinforce the importance for producers to use additional management strategies (e.g., control preharvest volunteer wheat) to manage this complex.

Keywords: wheat curl mite, *Aceria tosichella*, planting date, winter wheat, virus

The wheat curl mite (*Aceria tosichella* Keifer) is the only known vector of three viruses in wheat: Wheat streak mosaic virus (WSMV), Wheat mosaic virus (WMoV), and Triticum mosaic virus (TriMV). This wheat–mite–virus complex is the primary cause of disease loss in winter wheat production in the western Great Plains (Appel et al. 2007). Several factors can impact the severity of this disease complex. As mite movement into the field increases, the frequency of infested plants increases (Thomas and Hein 2003). Wheat infected prior to significant tillering is severely impacted and becomes stunted, yellowed, and rosetted (Hunger et al. 1992, Wegulo et al. 2008, Byamukama et al. 2012). Infections occurring in the spring after significant tillering are not as severe (Hunger et al. 1992, Byamukama et al. 2012).

Controlling volunteer wheat in the summer to break the green bridge of hosts that are necessary for mite and virus survival between wheat harvest and subsequent wheat emergence in the fall is the most effective management tactic for the wheat–mite–virus complex. However, controlling volunteer wheat is not always effective, and other important risk factors have been identified. For example, during the 1988 growing season, a high incidence of WSMV was reported in eastern Kansas with a low incidence of volunteer wheat (Christian and Willis 1993). Because of the potential loss associated with the wheat–mite–virus complex, multiple management tactics are necessary to reduce the impact of this complex.

Wheat varieties with resistance to the wheat curl mite have been developed; however, mite-resistant strains have developed and compromised their effectiveness (Harvey et al. 1995, 1999). WSMV resistance has been identified and transferred into wheat (Wells et al. 1973, 1982; Friebe et al. 1991; Gill et al. 1995); however, few virus-resistant varieties have been developed. 'Mace' was the first commercial variety released with resistance conferred by the *wsm1* gene (Graybosch et al. 2009). Mace was developed for its strong resistance to WSMV, but it was later shown to also be effective at reducing the impact of TriMV (Tatineni et al. 2010, Byamukama et al. 2012).

Planting date can have a significant effect on the level of severity of WSMV (Willis 1984, Hunger et al. 1992). It has been observed that early-planted wheat was more severely impacted by WSMV, whereas later-seeded wheat reduced the impact of WSMV (Willis 1984, Hansing et al. 1950). Early seeding of winter wheat increases the potential for wheat curl mite establishment and virus infection, and early virus infection can lead to greater impact on wheat. Hunger et al. (1992) found that early and late-planted winter wheat could be significantly impacted by mechanical inoculation of WSMV. Late-planted wheat inoculated in the spring was impacted more because of its limited growth stage, indicating that the maturity of plants at the time of infection may affect the impact of WSMV (Hansing et al. 1950, Hunger et al. 1992).

Even though previous work has identified the impacts of planting dates, these impacts have not been evaluated in combination with current virus-resistant varieties. The objective of this study was to evaluate the combined effect of planting date and the resistant variety Mace for their potential at reducing virus impact under high disease pressure. Unlike previous studies conducted on the effects of planting dates and virus impact, this study was conducted using natural populations of wheat curl mites to establish virus presence.

Materials and Methods

Field studies were conducted during two separate growing seasons at each of two locations. The 2007–2008 and 2008–2009 trials were conducted at the University of Nebraska Panhandle Research and Extension Center near Scottsbluff, NE. The 2009–2010 and 2010–2011 trials were conducted at the University of Nebraska Agricultural Research and Development Center near Mead, NE.

Treatments were arranged in a randomized complete block design with a split-plot arrangement of treatments and four replications. The main plot treatments were three planting dates chosen to simulate early (PD1), recommended (PD2), and late planting (PD3) dates. Split-plot treatments were three winter wheat varieties chosen based on their level of resistance to WSMV—Mace (resistant), 'Millennium' (mildly tolerant), and 'Tomahawk' (susceptible, AgriPro Sygenta Cereals). Each plot consisted of four, 2 -m rows with 0.3 -m spacing between rows. In 2007, plots were seeded on 30 August, 21 September, and 9 October. In 2008, plots were seeded on 27 August, 11 September, and 25 September. In 2009, plots were seeded on 25 August, 10 September, and 4 October. In 2010, plots were seeded on 27 August, 15 September, and 5 October.

In the summers of 2007 and 2008, a simulated volunteer winter wheat (Millennium) border (ca. 8-m wide) was planted after wheat harvest in late July around the area where the study plots were to be planted. Mites were infested into these plots by mid-August by collecting preharvest volunteer wheat that was heavily infested with mites and spreading the collected plant material over the simulated volunteer to allow mites to disperse to the growing wheat. Infested volunteer was collected in Kimball County, NE (2007), and Sheridan County, NE (2008).

Prior to the 2009–2010 and 2010–2011 trials, simulated volunteer winter wheat borders were planted around the plot area in May and again in mid-July. Each planting consisted of an 8 -m section surrounding the plots with the second planting seeded immediately adjacent to the subsequent plot area. The volunteer during the summer of 2009 was naturally infested with mites at low levels, and these mite populations increased through the summer into the fall. The May planting in 2010 became very heavily infested with mites from the neighboring plots just prior to harvest. Volunteer plants rapidly showed severe virus symptoms and soon died. As a result, simulated volunteer was planted again in late July. By late August few mites were present, so mite populations were bolstered with mites collected from volunteer wheat collected in western Nebraska (Cheyenne County) and spread over the plots.

Wheat curl mite movement was monitored in the fall of 2007, 2008, and 2010. Mite movement was evaluated around the plot area by using trap pots. Each trap pot consisted of three cone-tainers (4 cm in diameter, Steuwe and Sons Inc., Tangent, OR); each cone-tainer contained three to four Millennium wheat plants. Four trap pots were placed around the plots to monitor mite movement from the volunteer wheat. Wheat plants were grown in a greenhouse and covered with cages (5 cm in diameter and 50 cm in height) for 14 d prior to being brought to the field. Trap pots were exposed in the field for 7 d and changed weekly until late October when frost began killing the plants. To harvest trap pots, wheat plants were cut at soil level, placed in zip-lock bags, and stored at 4°C until mites were counted. Mite movement into the plots was measured by determining the percentage of trap plants with mites present.

During 2009–2010 and 2010–2011, mite presence in the screen was determined by randomly sampling 20 plants from the volunteer border approximately every 2 wk throughout the late summer and fall to monitor mite presence and abundance. All mite counts were done under a stereo-microscope at 30–40× to determine the number of mites on each of the plants.

Two methods were used to establish the severity of symptom development from virus infection. Relative chlorophyll readings were taken each year during the milk stage of the wheat by using a SPAD-502 Chlorophyll Meter (SPAD; Konica Minolta Sensing Inc., Ramsey, NJ). An average SPAD reading from 10 randomly selected flag leaves were taken from each plot. A visual yellowing rating was also taken at the early heading stage. An overall plot rating was based on a 0–5 scale (0 = no symptoms, 1 = some mosaic, 2 = significant mosaic, 3 = significant yellowing, with green caste remaining, 4 = only slight green remaining, 5 = yellow or brown). Virus presence was verified via double-antibody sandwich enzyme-linked immunosorbent assay (DAS-ELISA) for WSMV, WMoV, and TriMV (Tatineni et al. 2013, Byamukama 2013).

At harvest, the middle two rows were threshed from each plot, and the seed from each plot was then cleaned and weighed. Plot weights were converted to kg/hectare prior to analysis. Data were analyzed by using SAS software version 9.3 (SAS Institute Inc. Cary, NC). PROC MIXED was used to perform analysis of variance comparing the main and split-plot effects and their interactions, and least significant differences were used to establish differences between treatment means. Rank transformation of the nonparametric yellowing data was done by using PROC RANK with ranks from 1 to 36 for each year of the study (Conover and Iman 1981). The rank data were then analyzed by using PROC MIXED. Relationships between SPAD, yellowing rank, and yield were determined using PROC CORR and PROC REG. Temperature data were obtained for all 4 yr from the High Plains Regional Climate Center (hprcc.unl.edu; University of Nebraska–Lincoln). Data originated from established weather stations located near the plot sites.

Results

Average mean monthly temperatures varied across the years and locations of the study (Table 1). Average fall temperatures (September–November) were highest during 2010–2011 (11.3°C) and lowest during 2007–2008 (7.2°C). Spring temperatures (April– June) differed between the two locations with lower spring temperatures at Scottsbluff, NE, during 2007–2008 (12.8°C) and 2008–2009 (13.1°C) compared with Mead, NE, during 2009–2010 (17.5°C) and 2010–2011 (16.7°C).

Table 1. Average monthly, fall (Sept.–Nov.), and spring (April–June) temperatures (°C) during the winter wheat growing seasons for Scottsbluff, NE (2007–08, 2008–09), and Mead, NE (2009–10, 2010–11; data provided by the High Plains Regional Climate Center, University of Nebraska–Lincoln)

Month	2007–2008	2008–2009	2009–2010	2010–2011
Sept.	17.1	14.6	17.3	18.1
Oct.	10.3	8.1	7.3	12.4
Nov.	–5.9	3.6	–0.7	3.4
Sept.–Nov.	7.2	8.8	8.0	11.3
April	7.4	6.8	13.1	10.3
May	12.7	14.6	16.3	17.5
June	18.6	17.8	23.0	22.1
April–June	12.9	13.1	17.5	16.6

Mite counts from the trap cone plants for October of each year indicated differences in mite activity. The accumulated percentage of plants infested with mites in October 2007 (Scottsbluff) was 16.6%, whereas in 2008, 66.7% of plants were infested with mites. Trap cones in October 2010 (Mead) were 56% infested. No trap cones were collected during the fall of 2009; however, border plants were 100% infested with wheat curl mites compared with 85% in fall of 2010, indicating that mite activity was comparable each of these years. Trap cones provide only a relative estimate of mite activity, but from these data, we conclude that mite pressure in the fall was comparable for each for each of the last 3 yr of this study and less during the fall of 2007.

Each year the development of virus symptoms through the spring corresponded well with those expected from this virus complex. A greenish-yellow mosaic on the leaves expanded to extensive yellowing, stunting, and tiller spraddling in all severely infected plots. These observations plus positive DAS-ELISA assays for WSMV and TriMV confirmed that the wheat–mite–virus complex was the primary cause of the developing symptomology and subsequent yield losses for each year of the study. In addition, the resistant variety Mace had significantly higher SPAD readings (Figure 1), lower yellowing rank (Figure 2), and higher grain yields (Figure 3) compared with Millennium and Tomahawk. The relative differences between resistant Mace, mildly tolerant Millennium, and susceptible Tomahawk indicate the extent of virus pressure during each season of the study.

2007/2008 Scottsbluff, NE

Data analyses between years indicated that there was a significant year by planting date and year by variety interaction for SPAD, yellowing rank, and yield. Therefore, each year was analyzed separately. In 2007–2008, SPAD readings (Figure 1a) were not significantly different between planting dates ($F = 2.55$; df = 2, 6; $P = 0.1583$). Varieties were significantly different ($F = 369.54$; df = 2, 18; $P<0.0001$) indicating a significant virus impact. Mace (41.5) had higher SPAD reading than Millennium (22.1; $t = 16.02$; df = 18; $P<0.0001$), and Millennium had a higher SPAD reading than Tomahawk (8.9; $t = 11.02$; df = 18; $P<0.0001$). The interaction between planting date and variety was significant ($F = 3.34$; df = 4, 18; $P = 0.0328$), and this was due to an increase in SPAD reading for Millennium and Tomahawk across planting dates, whereas there was a decrease is SPAD reading for Mace in the late planting.

Yellowing ranks (Figure 2a) were not significantly different between planting dates ($F = 3.63$; df = 2, 6; $P = 0.0928$) with mean yellowing ranks of 15.1, 14.3, and 11.2 for early, recommended, and late planting, respectively. Significant variety differences were observed ($F = 87.68$; df = 2, 18; $P<0.0001$) with Mace (2.7) having the lowest rankings, followed by Millennium (14.7) and Tomahawk (23.3). The interaction between planting date and variety for yellowing ranks was approaching significance ($F = 1.95$; df = 4, 18; $P = 0.0686$). The reduction in yellowing ranks for Millennium from early to late planting dates likely contributed to this trend.

A significant difference in yield (Figure 3a) occurred between planting dates ($F = 10.63$; df = 2, 6; $P = 0.0107$). The recommended planting date yielded more (1,842 kg/hectare) than early (1,615 kg/hectare) and late (1,113 kg/hectare) planting dates. Varieties were also significantly different for yield ($F = 24.25$ df = 2, 18; $P<0.0001$). Mace (2,172 kg/hectare) yielded more than Millennium (1,247 kg/hectare) or Tomahawk (1,147 kg/hectare). The interaction between planting date and variety was significant ($F = 3.02$; df = 4, 18; $P = 0.0453$) due to increased yields for the recommended planting date for Millennium and Tomahawk. In comparison, early and recommended planting had no significant impact on Mace yields ($t = 0.72$; df = 18; $P = 0.4818$), but yields for the late planting dropped for all three varieties.

2008/2009 Scottsbluff, NE

SPAD readings increased significantly across the three planting dates ($F = 39.31$; df = 2, 6; $P = 0.0004$) at 16.5, 21.2, and 33.7 for early, recommended, and late planting, respectively (Figure 1b). Significant variety differences ($F = 36.16$; df = 2, 18; $P<0.0001$) were seen with Mace (32.8) having the greatest SPAD readings followed by Millennium (22.6) and then Tomahawk (15.9). The interaction between planting date and variety was also significant ($F = 2.87$; df = 2, 18; $P = 0.0420$). This interaction resulted because Millennium and Tomahawk had similar ($t = 0.41$ df = 18; $P = 0.6859$) and much lower SPAD readings than Mace for the first two planting dates. However, on the final planting date Millennium readings increased to close to those for Mace ($t = 0.45$; df = 18; $P = 0.6551$) and higher than Tomahawk ($t = 4.26$; df = 18; $P = 0.0005$).

Yellowing rankings (Figure 2b) differed significantly for planting dates ($F = 52.93$; df = 2, 6; $P = 0.0002$) with ranks decreasing from early (26.8) to late planting (11.1). Varieties were significantly different ($F = 62.99$; df = 2, 18; $P<0.0001$) with Mace (9.8) having significantly lower rankings than Millennium (20.0) and Tomahawk (25.8). The interaction between planting dates and varieties was significant ($F = 3.10$; df = 4, 18; $P = 0.0419$). This interaction was due to Millennium having increasingly less yellowing, and thus lower rankings, compared with Tomahawk for the recommended (19.4 vs. 26.5) and late (9.0 vs. 19.4) planting dates.

Yields (Figure 3b) were significantly different for planting dates ($F = 104.14$; df = 2, 6; $P<0.0001$) with increasing yields from early (324 kg/hectare) to recommended planting dates (1,115 kg/hectare; $t = \_2.35$; df = 6; $P = 0.0569$) and between recommended and late planting dates (2,379 kg/hectare; $t = \_6.23$; df = 6; $P = 0.0008$). Similar differences occurred for varieties ($F = 36.31$; df = 2, 18; $P<0.0001$) with Mace (1,958 kg/hectare) yielding significantly ($t = 9.82$; df = 18; $P<0.0001$) more than Millennium (1,079 kg/hectare). In addition, Millennium yielded significantly ($t = 2.08$, df = 18, $P = 0.0525$) more than Tomahawk (781 kg/hectare). There was no significant interaction between planting date and variety ($F = 1.39$; df = 4, 18; $P = 0.2760$).

2009/2010 Mead, NE

Severe virus impact reduced SPAD readings considerably for all treatment combinations. SPAD readings were significantly dif-

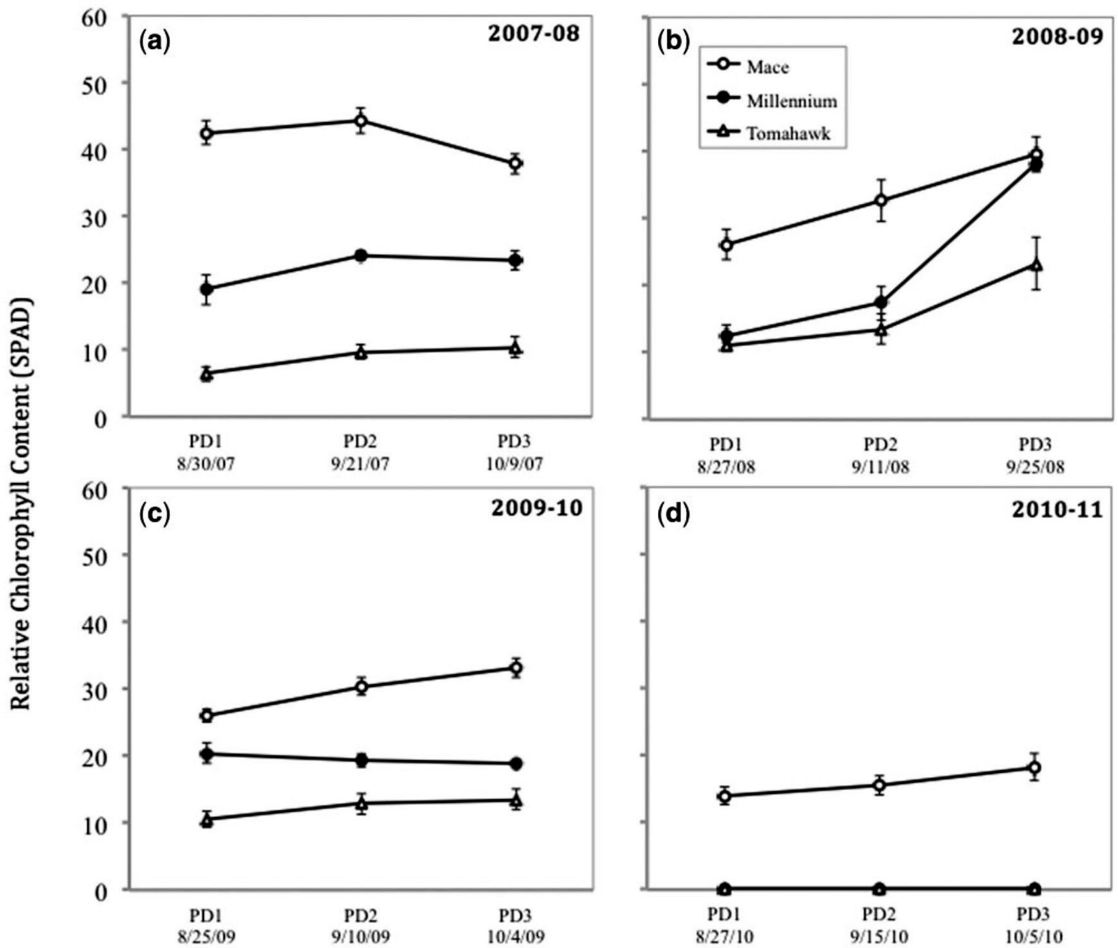

Figure 1. Relative chlorophyll readings (SPAD) for three winter wheat varieties across three planting dates for (a) 2007–2008, (b) 2008–2009, (c) 2009–2010, and (d) 2010–2011.

ferent between planting dates (F = 9.81; df = 2, 6; P = 0.0128; Figure 1c). A significant increase occurred between early (19.0), recommended (20.9), and late (21.8) plantings were seen; however, these differences were relatively small. Greater differences in SPAD readings were observed between varieties (F = 375.17; df = 2, 18; P<0.0001) with Mace (29.9) having significantly higher readings than Millennium (19.5; t = 15.98; df = 18; P<0.0001), and Millennium readings were significantly higher than Tomahawk (12.3; t = 11.28; df = 18; P<0.0001). The planting date by variety interaction was also significant (F = 7.51; df = 4, 18; P = 0.0010) due to a consistent increase in SPAD readings for Mace, whereas a decrease in Millennium and minimal increase in Tomahawk occurred across planting dates.

Yellowing rankings were significantly different between all varieties (F = 76.85; df = 2, 18; P<0.0001; Figure 2c). Mace (1.0) had significantly less yellowing than Millennium (14.0), followed by Tomahawk (23.8). There were no significant differences between planting dates (F = 2.08; df = 2, 6; P = 0.2063), and no significant interaction occurred between planting dates and varieties (F = 1.04; df = 4, 18; P = 0.4147).

As shown for the symptom evaluation data, severe yield reductions occurred across all treatment combinations. Significant differences between varieties occurred (F = 89.50; df = 2, 18; P<0.0001; Figure 3c). Mace (2,007 kg/hectare) yielded significantly more than Millennium (861 kg/hectare; t = 9.82; df = 18; P>.0001). In addition, Millennium yielded significantly higher than Tomahawk (516 kg/hectare; t = 2.95; df = 18; P = 0.0085). No significant difference occurred between planting dates (F = 0.59; df = 2, 6; P = 0.5824), and there was no planting date by variety interaction (F = 1.87; df = 4, 18; P = 0.1600).

2010/2011 Mead, NE

Extreme virus impact was seen in 2010–2011. SPAD readings (Figure 1d) were not significantly different between planting dates (F = 1.78; df = 2, 6; P = 0.2467). Significant variety differences (F = 297.03; df = 2, 18; P<0.0001) occurred with Mace having very low values that were significantly greater readings than both Millennium and Tomahawk, due to the death of these plants prior to evaluation. There was no significant planting date by variety interaction (F = 1.78; df = 4, 18; P = 0.1761).

Yellowing rankings for varieties were all significantly different (F = 301.66, df = 2, 18; P<0.0001), with Mace (6.5) having the lowest mean ranking, followed by Millennium (24.5) and Tomahawk (24.5). There were no significant differences in yellowing ranks (Figure 2d) between planting dates (F = 0.23; df = 2, 6; P = 0.7979), and there was no interaction occurred between planting date and variety (F = 0.25; df = 4, 18, P = 0.9046).

During 2010–2011, yield impact from virus infection was very dramatic with yield reductions of over 95% for all treatment plots compared with the higher yields seen earlier in this study. Mace yields were extremely low (43.0, 145.8, and 83.3 kg/hectare for the three planting dates, respectively), and Mace was the only variety that yielded harvestable grain (Figure 3d). Thus, no analysis of yield in this year was conducted.

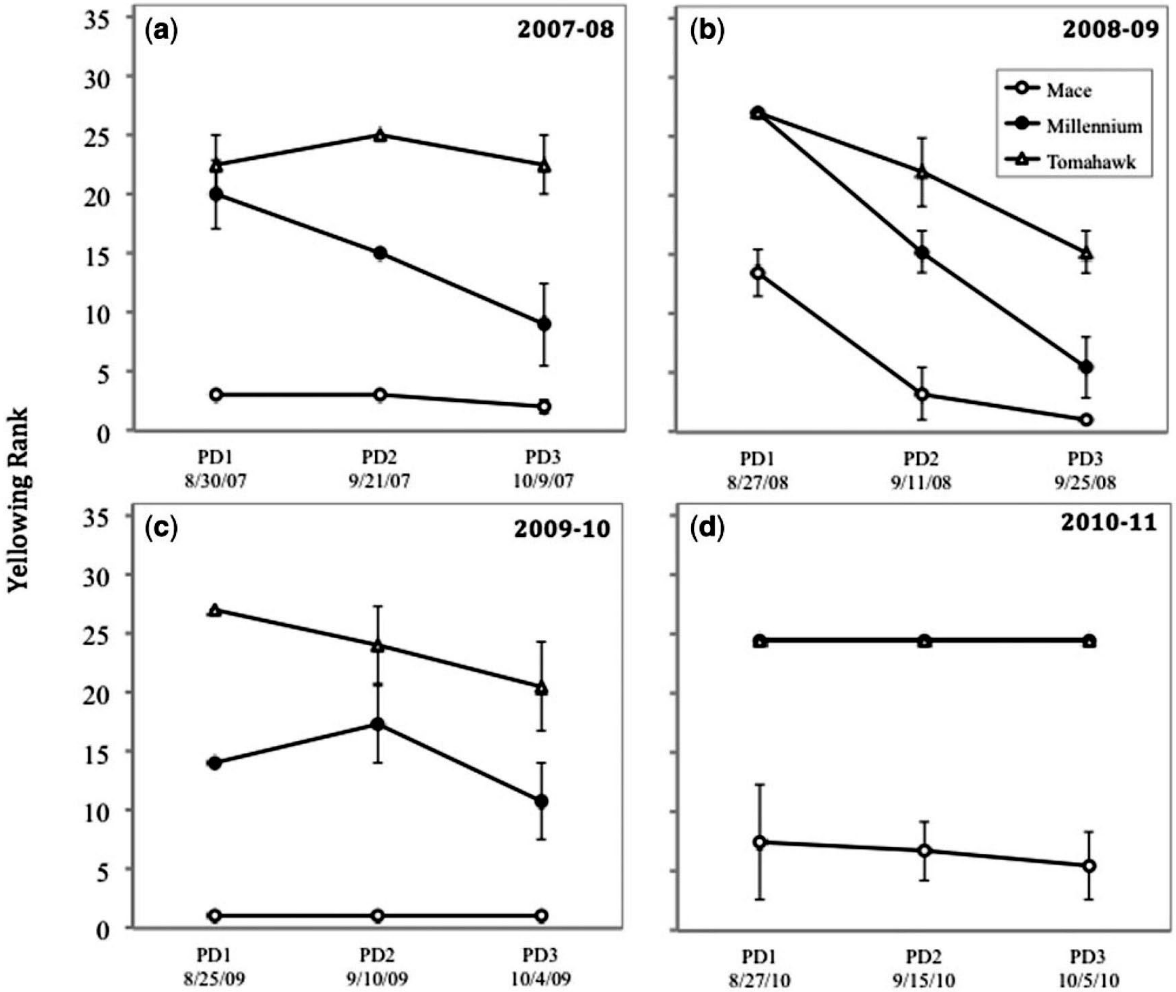

Figure 2. Yellowing ranks (based on 0–5 scale) for three winter wheat varieties across three planting dates for (a) 2007–2008, (b) 2008–2009, (c) 2009–2010, and (d) 2010–2011.

Correlation Between SPAD, Yellowing, and Yield

To evaluate the relationship between symptom expression and yield in this study, we correlated SPAD, yellowing rank, and yield (Table 2). A strong correlation was found between SPAD and yellowing rank ranging from –0.88 (2008–2009) to –0.98 (2010–2011). However, SPAD and yellowing rank differed in their correlation with yield with the highest and most consistent correlations occurring between SPAD and yield. SPAD-yield correlation coefficients ranged from 0.66 (2007–2008) to 0.88 (2008–2009), and when analyzed across all years the correlation was 0.82. The correlation between yellowing rank and yield was reasonably consistent (range –0.53 to –0.86); however, when correlated across all years the correlation dropped considerably to –0.63, indicating greater differences between years in this relationship.

To further understand the relationship between SPAD and yield, a regression analysis was run for each year of the study (Figure 4). Parameter estimates and R2-values were similar for 2008–2009 and 2009–2010. In 2007–2008, a lower slope and a higher intercept were observed along with a considerably lower R^2. Regressions were not run on the 2010–2011 data due to a lack of harvestable grain in two of the three varieties. The overall regression (without 2010–2011 data) was strong ($R^2 = 0.586$) considering the differences in yield impacts between years.

Discussion

Viruses transmitted by the wheat curl mite were the primary cause of yield loss for each year of the study. This is supported by the positive virus presence in ELISA assays each year, extensive mite presence observed in the plots, and the strong development of virus-related symptoms in all significantly impacted plots. In addition, no other significant disease or insect presence was observed in the plots during these study years. The source for virus was obtained through natural infestation of wheat curl mites and spread throughout all plots randomly, and as a result, there was no virus-free treatment. Data presented by Graybosch et al. (2009) showed that Mace and Millennium had statistically similar yields with no virus pressure. In contrast, we found significant symptomology differences (SPAD, Figure 1; yellowing rank, Figure 2) and grain yield (Figure 3) between Mace and Millennium for each year the study. The relative differences between these two varieties indicate considerable pressure from this virus complex.

Of the two management tactics evaluated, winter wheat variety provided the most consistent impact on symptom expression (i.e., SPAD, yellowing rank) and yield response for each year of the study. The resistant variety Mace showed reduced virus symptoms and yielded more than Millennium and Tomahawk for all years and planting dates. Byamukama et al. (2012) found similar differences

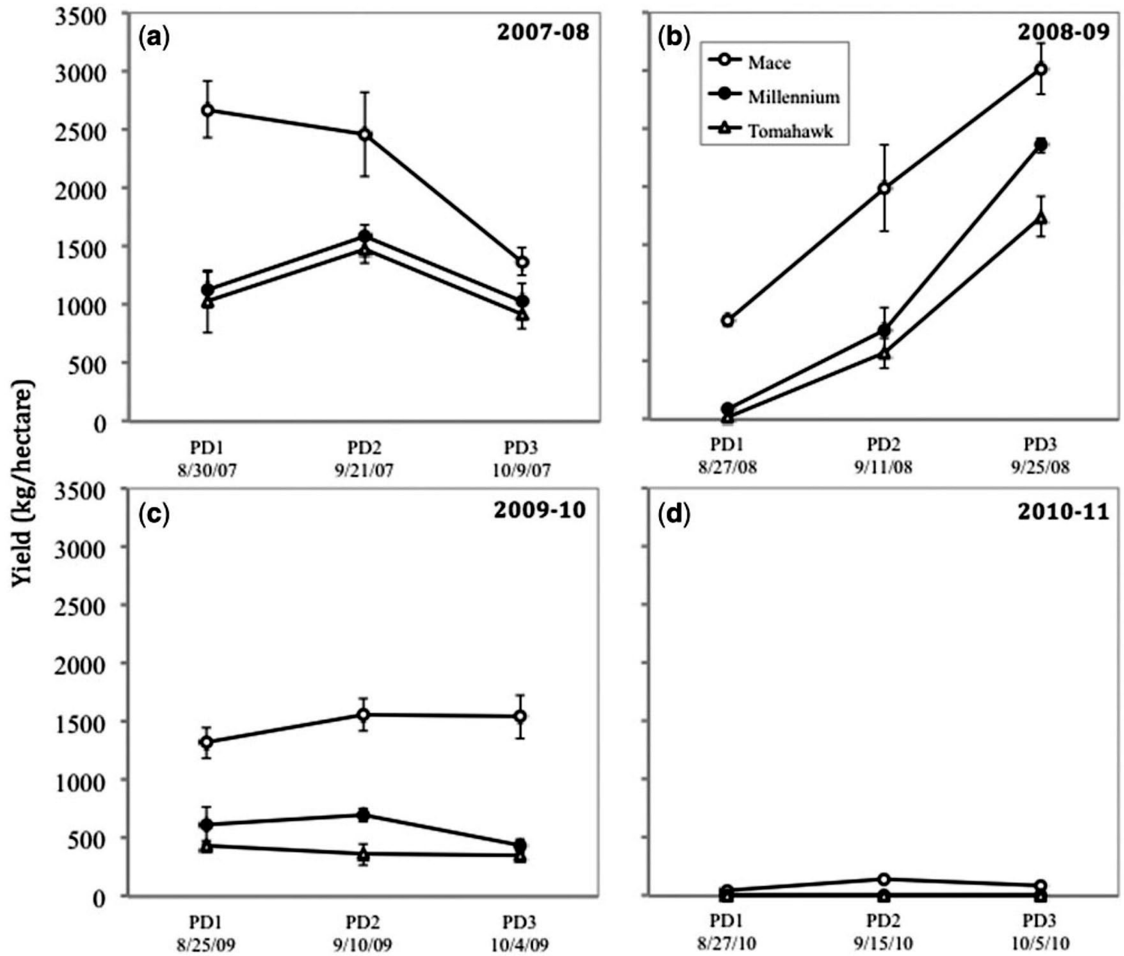

Figure 3. Yield for three winter wheat varieties across three planting dates for (a) 2007–2008, (b) 2008–2009, (c) 2009–2010, and (d) 2010–2011.

Table 2. Correlation coefficients (r) between SPAD, yellowing rank, and yield for each year and all years combined

Variables	2007–2008	2008–2009	2009–2010	2010–2011	All years
SPAD vs. Yield	0.6628	0.8782	0.8673	0.8096	0.8202
YelRank vs. Yield	–0.5329	–0.8571	–0.7870	–0.8017	–0.6338
SPAD vs. YelRank	–0.9070	–0.8751	–0.8765	–0.9836	–0.8069

between Mace and Millennium using fall mechanical inoculations under field conditions of single and double infections of WSMV and TriMV. Even though Mace had the highest yields each year of this study, its total yield was very low during both 2009–2010 and 2010–2011 seasons. Significant yield losses for Mace during these two years could be attributed to its temperature-sensitive resistance to WSMV with resistance breaking down at temperatures near 27°C (Seifers et al. 1995). Once temperatures exceed this threshold, Mace shows susceptibility similar to other varieties that do not carry the resistant gene (Seifers et al. 1995). In addition, Tatineni et al. (2010) found that WSMV accumulated at moderate levels in Mace at 20 to 26°C. In this study, temperatures during the 2009–2010 and 2010–2011 seasons were the highest and may have negatively impacted virus response in Mace. This demonstrates that the resistance in Mace may not be adequate under warmer environmental conditions.

Planting date had less of an impact than variety on symptom expression and yield with the most significant effects occurring during the 2008–2009 season. There was no interaction between variety and planting date for yield during the 2008–2009 season due to an increased yield for all varieties from early to late planting. These results indicate the need to incorporate both management strategies, as the resistant variety Mace was significantly impacted by virus in the early planting date during that season. A similar trend was observed during the 2007–2008 season for the early and recommended planting dates, resulting in increased yields for mildly tolerant and susceptible varieties for the recommended planting date. This increase was not observed for Mace, as its yield remained high across both planting dates. In contrast to 2008–2009, late planting during 2007–2008 resulted in decreased yields for all varieties compared with early and recommended planting dates. This decrease in yield did not correspond to reduced yellowing rank or SPAD reading indicating reduced virus symptoms, thus virus was likely not the primary cause of this decrease. Late-planted wheat during the 2007–2008 season was negatively impacted by delayed planting. Recommended planting dates for western Nebraska are in mid- September, and this late planting date (October 9), combined with cool temperatures (Table 1), resulted in reduced tillering and fall growth prior to the onset of winter, and thus, reduced yield potential.

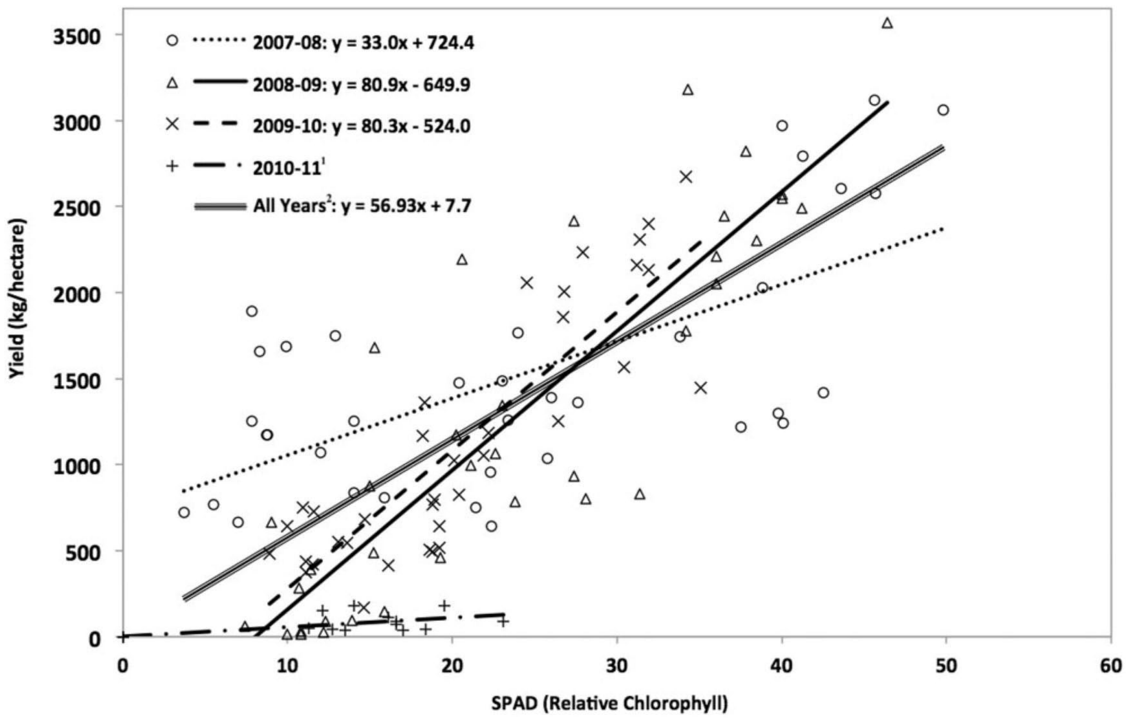

Figure 4. Regression relationships between relative chlorophyll readings (SPAD) and yield with trend lines for each year of the study.

1. No equation was provided for 2010–2011 data due to extreme virus impact.
2. The equation labeled "all years" includes all years of the study except 2010–2011.

R^2-values:
0.44 (2007–2008),
0.77 (2008–2009),
0.75 (2009–2010),
and 0.59 (all years).

Previous authors have documented planting date impacts similar to those found in 2007–2008 and 2008–2009. Willis (1984) published a summary of a 10-yr study on planting dates in South Dakota by W. S. Gardner and concluded that early-planted wheat was most significantly impacted by WSMV. Hunger et al. (1992) found that early and recommended planting dates were severely impacted by fall inoculations but not as readily impacted by spring inoculations. Late-planted wheat was impacted more by spring inoculations because of limited fall growth and infection occurring prior to significant tillering early in the spring. In addition, Hansing et al. (1950) observed that wheat planted early or late in the fall was significantly impacted compared with those seeded at the recommended planting date. These studies as well as data from the first two years of the current study indicate the importance of avoiding early planting. Planting date is important for management of this complex; however, very high virus pressure (2009–2010 and 2010–2011) and conducive environmental conditions can negate the impact of planting date.

This study was not designed to test the impact of temperature on these management strategies; however, the virus impact in this study was consistent with the environmental conditions (i.e., fall and spring temperatures) observed. Cooler fall temperatures in 2007 (Table 1) may have impacted late-planted wheat through reduced tillering prior to the onset of winter, thus contributing to the poor yields for the late-planted wheat that year. The lower September–November average temperatures in 2007 may have also reduced the virus impact in the other planting dates, as virus impact in 2007–2008 was the lowest in the study. However, we also noted that mite pressure was also lower in this year. Cool spring conditions in 2007–2008 and 2008–2009 would have been favorable for Mace, as its resistance is temperature sensitive (Seifers et al. 1995). This supports the higher yields for Mace in 2007–2008 and 2008–2009. The warmer temperatures seen in 2009–2010 and 2010–2011 may have increased virus impact for all treatments and reduced the stability of virus resistance and suppressed Mace yields. Further research is needed to validate the impact of the wheat–mite–virus complex under different fall and spring temperature regimes.

The wide range of virus impacts between seasons allows us to evaluate the ability of virus symptoms to predict potential yield losses. A comparison of correlations between symptom development (SPAD, yellowing rank) and yield indicated that SPAD (r = 0.82) was a better predictor of grain yield than yellowing rank (r = –0.63). The lower correlations between yellowing rank and yield could have been due to a variety of factors. The yellowing rating is based on a subjective rating scale that could be influenced by evaluator's experience level and differing interpretations of the visual symptoms. In addition, the 0–5 rating scale limits the separation of symptoms to only a few categories under high virus pressure and, when correlated with yields, limits the resolution power of the data. In contrast, SPAD readings are not subjective and provide a continuous variable that can account for slight changes in symptoms. If taken in a consistent manner, SPAD readings should not vary between evaluators. Typically, SPAD readings above 40 are indicative of healthy wheat plants. Values between 30 and 40 are typical of plants showing the initial yellowing symptoms resulting from virus infection. Plants with SPAD values between 20 and 30 are heavily symptomatic (yellowed). SPAD values below 20 coincide with extreme virus symptoms with little if any green remaining in the plant. Comparable SPAD regression equations and R_2s were obtained for 2008–2009 and 2009–2010 even though they occurred under distinctly different growing conditions. A lower R_2 value and different regression equation were found during 2007–2008, but this may be attributed to the agronomic impact (i.e., reduced yield) from reduced tillering in late-planted wheat. SPAD readings are a measure of the relative chlorophyll of the plant (Uddling et al. 2007), and as a result, they can be influenced by a variety of other factors such as disease, insect feeding, and nutrition. In addition, the wheat development stage at the time of SPAD read-

ings could influence correlations, as symptoms will develop over a period of time and virus expression will be strongly affected by temperature. It is important to note that these same factors would influence the yellowing ratings. Overall, SPAD readings provide a means to objectively compare symptom development or expression, reducing the variation associated with more subjective ratings.

The results from this study demonstrate the potential for extreme yield impacts from this virus complex. This is the first study to document the combination of variety and planting date for management of the wheat–mite–virus complex using natural wheat curl mite infestations to create virus infection. We established mite source populations to simulate high risk scenarios to insure significant virus impact. The impact of these tactics may vary across regions and cropping systems. Planting date and variety were shown to be suitable management tactics for this complex; however, these strategies are not effective at mitigating virus impact under high virus pressure and favorable environmental conditions. This study, as well as previous studies, demonstrates the importance of planting at the recommended planting date with positive yield responses from both resistant and susceptible varieties. In order to reduce the impact from this complex, these tactics should be applied in combination. However, additional management strategies are necessary, and the primary goal of these strategies should be to manage over summering hosts of the mites and virus, especially volunteer wheat.

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