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Developing the framework for a risk map for mite vectored viruses in wheat resulting from pre-harvest hail damage

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ABSTRACT

There is a strong economic incentive to reduce mite-vectored virus outbreaks. Most outbreaks in the central High Plains of the United States occur in the presence of volunteer wheat that emerges before harvest as a result of hail storms. This study provides a conceptual framework for developing a risk map for wheat diseases caused by mite-vectored viruses based on pre-harvest hail events. Traditional methods that use NDVI were found to be unsuitable due to low chlorophyll content in wheat at harvest. Site-level hyperspectral reflectance from mechanically hailed wheat showed increased canopy albedo. Therefore, any increase in NIR combined with large increases in red reflectance near harvest can be used to assign some level of risk. The regional model presented in this study utilized Landsat TM/ETM+ data and MODIS imagery to help gap-fill missing data. NOAA hail maps that estimate hail size were used to refine the area most likely at risk. The date range for each year was shifted to account for annual variations in crop phenology based on USDA Agriculture statistics for percent harvest of wheat. Between 2003 and 2013, there was a moderate trend ($R^2 = 0.72$) between the county-level insurance claims for Cheyenne County, Nebraska and the area determined to be at risk by the model (excluding the NOAA hail size product due to limited availability) when years with low hail claims (<400 ha) were excluded. These results demonstrate the potential of an operational risk map for mite-vectored viruses due to pre-season hail events.

1. Introduction

Wheat (*Triticum aestivum* L.) is a major economic crop in Nebraska ranking fifth in terms of cash receipts (Nebraska Deparment of Agriculture, 2012) and third in volume exported (Van Meter et al., 2012). Thus, there is a strong economic incentive to minimize loss due to diseases. Economically important diseases of wheat include those caused by viruses transmitted by the wheat curl mite (WCM, *Aceria tosichella* Keifer). These viruses are wheat streak mosaic virus (WSMV; Slykhuis, 1955), Triticum mosaic virus (TriMV; Seifers et al., 2009; Tatineni et al., 2009), and Wheat mosaic virus (WMoV; Seifers et al., 2007). Surveys of wheat fields in the Great Plains of the United States determined WSMV to be the most prevalent of the three viruses (Burrows et al., 2009; Byamukama et al., 2013). Single, double, or triple infections of wheat by the viruses were confirmed, with a high frequency (91%) of co-infection with WSMV and TriMV (Burrows et al., 2009; Byamukama et al., 2013). Co-infection of wheat by WSMV and TriMV has been shown to decrease yield by 81–96% (Byamukama et al., 2014).

WCM-transmitted viruses are commonly found throughout the Great Plains of North America (Burrows et al., 2009), and the viruses have recently spread outside of North America (Schubert et al., 2015; Ellis et al., 2003; Truol et al., 2004). However, the highest risk for WSMV/TriMV outbreaks is volunteer wheat that emerges before harvest as a result of hail storms. The WCM has a short life cycle (egg to adult in 7–10 days) and cannot survive for more than a few days off green plants (Wosula et al., 2015). Volunteer wheat acts as a “green bridge” host for the WCM and

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viruses between summer harvest and winter wheat planting in the fall (Gibson and Painter, 1956; Shahwan and Hill, 1984). If the volunteer wheat survives until planting, WCMs disperse, aided by wind or air currents, to the emerged winter wheat crop and transmit the viruses (Somsen and Sill, 1970). Controlling volunteer wheat through herbicide application or tillage before emergence of the winter wheat crop minimizes the risk of virus infection (Thomas et al., 2004). Therefore, identification of areas where pre-harvest volunteer wheat is likely to occur due to hail damage will facilitate timely control of volunteer wheat.

Hail damage has been successfully identified in different agricultural settings by evaluating changes to the spectral properties of vegetation (Gallo et al., 2012; Parker et al., 2005; Zhao et al., 2012). Healthy vegetation has low reflectance in the visible range of the electromagnetic spectrum due to absorption by pigments such as chlorophyll, carotenoids, and anthocyanins. Low reflectance in the visible range is contrasted by high reflectance in the near-infrared (NIR) region due to scattering at the leaf cellular level and canopy structure (Gitelson, 2011). The normalized difference vegetation index (NDVI) measures the difference between canopy absorption and scattering (Tucker, 1979) and is very sensitive to changes in green (photosynthetically active) leaf area index (gLAI) values below 3 $m^2\ m^{-2}$ (Viña et al., 2011). Hail damage alters crop canopy structure and reduces absorption by pigments, such as chlorophyll. NDVI has been used in many studies to detect hail swaths due to its sensitivity to these changes (Erickson et al., 2004; Kalb and Bentley, 2002; Molthan et al., 2013; Peters et al., 2000). However, many of these studies were done in the middle of the growing season when canopy chlorophyll is high. The period when wheat grain is most likely to germinate if dislodged from heads by hail occurs at the end of the growing season when NDVI is typically low. Therefore, an approach using changes in NDVI may not be suitable, and alternatives should be explored.

The goal of this study was to develop a framework for using remote sensing products to identify high risk areas for transmission of WCM-vectored viruses to fall-planted wheat in the Nebraska Panhandle. Such products will allow farmers to execute management strategies to minimize the risk of future WSMV outbreaks. The specific objectives were to 1) identify the spectral behavior of wheat impacted by hail, 2) select suitable raster-based data that can identify hail events and hail damage, and 3) develop a series of risk maps for Cheyenne County, Nebraska, U.S.A. between 2003 and 2013.

2. Materials and methods

2.1. Mechanically hailed plots

Rainfed 'Pronghorn' winter wheat was mechanically hailed using a hail simulator at the High Plains Ag Lab (41.23019N, 102.99962W) near Sidney, Nebraska, U.S.A. Treatments were arranged in a randomized complete block, split-plot design with eight replications. The main plot treatments were four different hail dates during the heading stages of wheat; middle milk (Zadoks 75), early dough (Zadoks 83), soft dough (Zadoks 85), and hard dough/ripe (Zadoks 87/91). Example photographs of the hailed plots are in Fig. 1. The split-plot treatments were uncaged and caged (2 m $\times$ 2 m) to represent rapid and slow drying conditions, respectively, following the hail. Split-plot cages were placed one day after the hail treatment and removed seven days later. Plots were watered using a garden hose sprinkler with ca. 25 mm at 0, 2, and 4 days after hail application to simulate the expected rainfall accompanying a hail event.

Hail treatments were applied with a hail simulator attached to and powered by a tractor. For each plot, five 9 kg ice bags were placed in a hopper at the top of the machine and fed into a vertical feeder housing containing a rotating horizontal cylinder with spikes that crushed the ice into 4–5 cm pieces. Ice was then propelled from the machine at approximately 80 km h^{-1} through a 20-cm diameter hose powered by a hydraulic air seeder fan. The hose was directed toward the wheat across the entire plot (2 m $\times$ 2 m) in a continuous motion at a 45-degree angle for uniformity between plots.

The spectral behavior of each plot was recorded one day prior to the hail application and at 1, 7 and 14 days after hail application. An adjacent field that did not have split-plot cages was used for reflectance measurements at harvest. Spectral behavior was recorded using a dual fiber system containing two USB2000 radiometers (Ocean Optics Inc. Dunedin, FL, U.S.A.). These radiometers have a sampling range of 400–900 nm, an interval of 0.3 nm, and a spectral resolution of 1.5 nm. The upwelling fiber had a 25° field of view and was held 1 m above the top of the canopy. This provided an area with a diameter of approximately 0.44 m. The downwelling fiber was equipped with a cosine corrector to measure incoming irradiance. The two radiometers were inter-calibrated using a white Spectralon panel (Labshere, Inc., North Sutton, NH, U.S.A.). The fibers were attached to a painter's pole to minimize the influence of the user on the reflectance and the pole was stabilized using a tripod. For more details on the radiometer system see Rundquist et al. (2004). Each reflectance reading was an average of eight scans collected over eight random positions over each plot. The plot level reflectance was an average of these readings over both caged and uncaged plots ($n = 128$). Since the plots had not been divided yet, there were fewer reflectance readings at the start of the experiment ($n = 64$). Similarly, there was an increased number of reflectance observations at harvest ($n = 296$) to fully characterize the variability of the adjacent field. The median reflectance from each of the split-plot treatments was used to determine the plot-level reflectance. For statistical summaries, the hyperspectral reflectance was used to simulate the Landsat 8 spectral response curve where the standard error (SE) and coefficient of variation (CV) were calculated using Excel (v. 2013, Microsoft Corporation, Redmond, WA, U.S.A.) and the analysis of variance (ANOVA) between treatments was determined using R (v. 3.2.2 R Development Core Team, 2015). The fixed effect for the ANVOA tests was hail treatment and heading stage was a random effect.

2.2. Raster inputs for the risk model

Three remotely sensed products were utilized for this study: a NOAA hail size estimation product, Landsat Surface Reflectance from the Climate Data Record (CDR), and Moderate-resolution Imaging Spectroradiometer (MODIS) surface reflectance. In general, the NOAA hail size product provides information about the presence of hail in an area and the reflectance products identify changes in albedo and the details of the model are outlined in Fig. 2. The NOAA hail product is an optimal candidate for inclusion in the model. This product is created by blending remotely sensed three dimensional storm intensity data from multiple WSR-88D radars covering the area of interest with the vertical atmospheric temperature profile (Lakshmanan et al., 2007; Smith and Lakshmanan, 2011). This provides an estimate of maximal hail size aloft in a thunderstorm, with a horizontal resolution of 0.01° longitude by 0.01° latitude (approximately 1 km^2). Although the product is intended for diagnosis of hail size aloft, Ortega et al. (2009) showed a strong relationship between predicted and measured hail size. The NOAA hail product is produced every two minutes; however, this resolution is much more frequent than necessary for seasonal use. One product representing maximal hail size over the period of highest risk should be sufficient for the model.