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Low-level jet streams associated with spring aphid migration and current season spread of potato viruses in the U.S. northern Great Plains

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Abstract

Green peach aphid, *Myzus persicae* (Sulzer), is the principal and possibly sole vector of *Potato leafroll virus* (PLRV) and a key vector of *Potato virus Y* (PVY) in the U.S. northern Great Plains. Current season spread of PLRV and PVY in seed potato depends primarily on flight activity of winged aphids and the availability of virus inoculum. *M. persicae* does not overwinter outdoors in the northern Great Plains, populations are reestablished each year by spring immigrants from the south. The objective of this research was to relate spring low-level jet (LLJ) streams to intensity of *M. persicae* flight activity and current season spread of PLRV and PVY. Synoptic weather maps were used to identify LLJ events that could have brought aphids into the northern Great Plains and to record the timing and duration of each event from 1 May to 30 June. HYSPLIT (Hybrid Single-particle Lagrangian Integrated Trajectory), a trajectory analysis model developed by the National Oceanic and Atmospheric Administration and Australian Bureau of Meteorology, was used to track pathways of air particles to their source. Captures of *M. persicae* and other potential vector species by a regional aphid trapping network (*Aphid Alert*) from 1992 to 1994 and 1998 to 2003 were used as measures of aphid flight activity. Results from winter grow-outs of the Minnesota Seed Potato Certification Program were used as measures of available PLRV and PVY inoculum. As a possible surrogate for aphid flight activity we used data on spring wind events to predict current season seed lot rejections due to PLRV and PVY. Statistical models were developed relating frequency and duration of spring wind events to subsequent *M. persicae* abundance and severity of PLRV and PVY spread in the northern Great Plains. Results showed that the cumulative LLJ duration fit best with cumulative *M. persicae* capture through the first week of August (R^2 ranging from 0.597 to 0.883), and the current season spread of PLRV fit best with inoculum and cumulative *M. persicae* capture through the first week of August ($R^2 = 0.75$, $P = 0.015$). LLJ duration did not reliably predict seasonal abundance of PVY vectors other than *M. persicae*. The model for prediction of PVY using LLJ duration and PVY inoculum was considerably less reliable ($R^2 = 0.30$, $P = 0.34$) although using both *M. persicae* capture through the first week of August and PVY inoculum fit better ($R^2 = 0.39$, $P = 0.231$).

Keywords: *Myzus persicae*; *Potato leafroll virus*; *Potato virus Y*; Low-level jet stream

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1. Introduction

Historically, the northern Great Plains, specifically northwestern Minnesota and eastern North Dakota, has been one of the most important regions of seed potato production in the U.S. Prior to 1996, this region produced more than 20,000 ha of certified seed potatoes each year. By 2001, seed potato production in the northern Great Plains was only 11,700 ha. This decline in seed potato production occurred in conjunction with sustained and devastating economic losses resulting from concurrent epidemics of *Potato leafroll virus* (PLRV) and *Potato virus Y* (PVY).

PLRV and PVY are aphid-transmitted viruses. Transmission patterns of these two viruses differ, PLRV is persistent and circulative in the vector and the combined time from acquisition by a naïve vector until that vector can transmit is measured in days. In contrast, PVY is a non-persistent, stylet-borne virus and a naïve vector can acquire and transmit the virus in just seconds. In the northern Great Plains, PLRV is transmitted almost exclusively by green peach aphid, *Myzus persicae* (Sulzer), whereas PVY has numerous potential vectors. Species suspected to be important in transmission of PVY in the northern Great Plains include bird cherry-oat aphid, *Rhopalosiphum padi* (L.), corn leaf aphid, *Rhopalosiphum maidis* (Fitch), English grain aphid, *Macrosiphum avenae* (Fabricius), greenbug, *Schizaphis graminum* (Rondani), potato aphid, *Macrosiphum euphorbiae* (Thomas), buckthorn aphid, *Aphis nasturtii* (Kaltenbach) and soybean aphid, *Aphis glycines* (Matsumura) (DiFonzo et al., 1997; Suranyi, 2002; Davis et al., 2005).

From 1992 to 1994 and again from 1998 to 2003, the University of Minnesota operated an aphid trapping network, *Aphid Alert*, to provide the region's seed potato growers with near real-time information on aphid flight activity (Radcliffe and Ragsdale, 2002). Hladilek et al. (2006) showed that current season spread of PLRV and PVY, as measured by potato seed lot rejections (Seed Potato Certification Program of the Minnesota Department of Agriculture) for recertification in the annual winter grow-outs, could be modeled using linear regression models incorporating vector abundance (cumulative capture of key vector species per trap in the *Aphid Alert* network) and inoculum levels (proportion of seed lots exceeding virus thresholds for recertification in the previous years seed potato crop).

Most of the aphid species presumed to be important in transmission of PLRV and PVY in the northern Great Plains cannot survive the regions harsh winters and are reestablished each spring by long distance migrants. Aphids are weak fliers, thus, migratory aphid species are highly dependent on the movement of air currents such as low-level jet (LLJ) streams.

Physical factors that terminate migration of aphids or other biota include gravity, cold temperatures, precipitation, depletion of the insect's energy resources, impaction, or combinations of the above (Pedgley, 1982; Westbrook and Isard, 1999). The northern edge of LLJs usually cause rainfall in the Great Plains (Schubert et al., 1998; Wu and Raman, 1998), which can be a potential deposition mechanism for migratory aphids transported on LLJs. This suggested that the frequency and duration of spring LLJ events could be used to predict summer vector abundance and thus the extent of current season spread of potato viruses in the northern Great Plains.

2. Material and methods

2.1. Wind vectors

Archived weather maps of wind vector data from 1 May to 30 June, 1992 to 1994 and 1998 to 2003 were used to identify southerly LLJs that might transfer aphids to the northern Great Plains. The 2 h Nested Grid Model (NGM, 1992–1994) and the 3 h Eta Data Assimilation System (EDAS, 1998–2003) from the National Centers for Environmental Prediction (NCEP) were used to track movement of air currents through time (Rolph, 2003). The Nested Grid Model was a relatively coarse model with a spatial resolution of 180 km horizontally, and 10 vertical levels from sea surface to about 434 Sig. The vertical coordinate used in the NGM model was the sigma level. The Nested Grid Model was replaced by EDAS in 1997. The spatial resolution of EDAS is 80 km horizontally with 22 vertical levels from sea surface to 50 hPa.

2.2. LLJ criteria and duration

LLJs during May and June in 1992 to 1994 and 1998 to 2003 were identified from wind vector maps at 1500 m from the NGM and EDAS models which can be accessed through website: http://www.arl.noaa.gov/ready/amet.html (accessed 25 March, 2006). Wind vector maps were created though the website from 1 May to 30 June during the study years. Criteria used to identify LLJs that could transport aphids into the northern Great Plains included: (1) wind maxima greater than 12 m s^{-1} at 1500 m above ground level (AGL); (2) event durations greater than 12 h; (3) wind direction from SE (135°) to SW (225°) and (4) decreased wind speed (>4 m s^{-1}) area over the northern Great Plains. The first and the last date that LLJ criteria were satisfied and the duration (h) that these criteria were continuously satisfied were recorded.

2.3. Daily weather maps

Daily weather maps at 1200 UTC (7:00 a.m. EST), produced by the NCEP, Hydrometeorological Prediction Center were used to analyze the synoptic conditions, including pressure field distribution and front locations from 1 May to 30 June, 1992 to 1994 and 1998 to 2003.

2.4. Rainfall data

Precipitation data from May to June, 1992 to 1994 and 1998 to 2003 were downloaded from the National Climatic Data Center (NCDC, 2004) from 36 locations in 19 counties in the northern Great Plains. Average daily precipitation was calculated across all locations.

2.5. Aphid capture data

Data on seasonal aphid flight activity within the major seed production region of the northern Great Plains (9 counties in northwest Minnesota and 10 counties in northeast North Dakota) were obtained from the eight *Aphid Alert* trap locations that were common to the years 1992–1994 and 1998–2003: Baker, Climax, Karlstad and Williams in Minnesota, and Cando, Hoople, Rolette and Walhalla in North Dakota (Fig. 1). One 2.3 m suction trap (Allison and Pike, 1988) and two green tile-pan traps (DiFonzo et al., 1997) were operated at each location. Traps were emptied weekly and the aphids collected were sorted into species and counted. For purposes of the present study, attention was focused on two potato colonizers, *M. persicae* and *M. euphorbiae*, both potential vectors of both PLRV and PVY, and four cereal aphids, *R. maidis*, *R. padi*, *M. avenae*, *S. graminum*, each potential vectors of PVY. *A. nasturtii* and *A. glycines* were not considered in this study because *A. nasturtii* was not commonly represented in the trap captures during the study period, and *A. glycines* is newly established in the region and was abundantly captured only in 2003. Aphid data were summarized, by species, as cumulative capture through July, each individual week of August, and for the entire season.

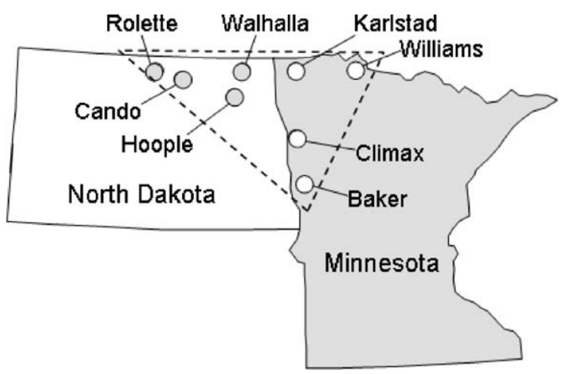


Fig. 1. *Aphid Alert* network trap locations common to 1992–1994 and 1998–2003, triangle encompasses Minnesota and North Dakota portions of northern Great Plains seed potato production area.

2.6. The HYSPLIT model

HYSPLIT, a model developed by the Air Resources Laboratory (ARL), National Oceanic and Atmospheric

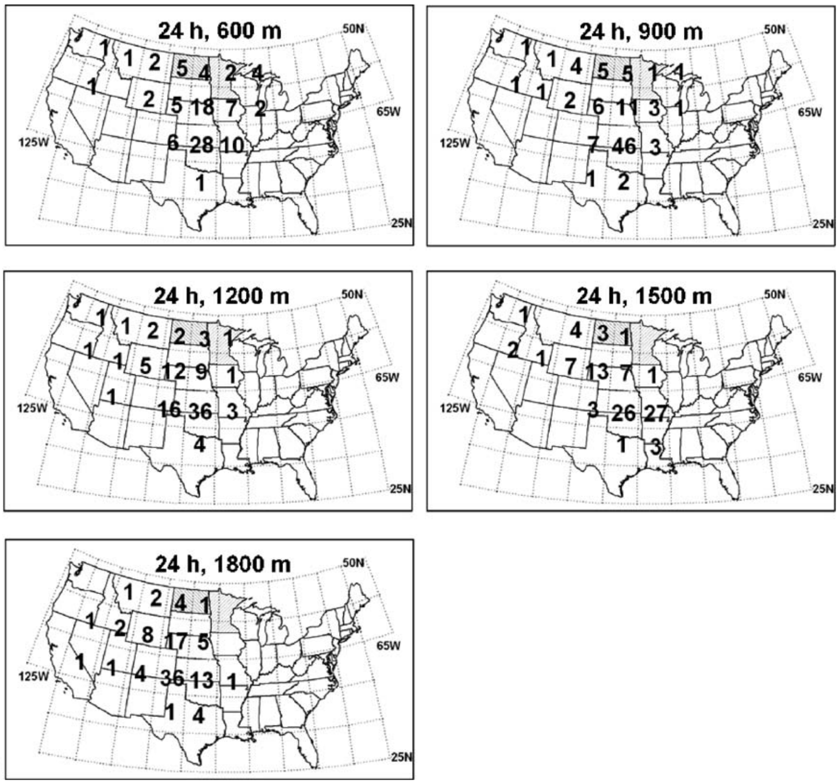
Table 1
Frequency and duration of low-level jet (LLJ) streams identified as suitable for long distance transport of *Myzus persicae* to the northern Great Plains from 1992 to 1994 and 1998 to 2003

Year	Date	Duration (h)
1992	5/09–5/10	18
	5/20–5/21	32
	6/16–6/17	30
1993	5/08–5/09	22
	6/12–6/13	24
1994	5/16–5/19	56
	5/19–5/21	36
1998	5/13–5/15	42
	5/27–5/28	18
	6/17–6/18	31
1999	5/02–5/05	39
	5/10–5/11	24
	5/29–5/30	36
	6/03–6/04	24
	6/08–6/09	12
	6/18–6/19	18
	6/21–6/23	36
	6/25–6/26	24
2000	5/05–5/06	30
	6/09–6/10	27
	6/19–6/20	27
2001	5/05–5/06	15
	6/25–6/26	27
	6/28–6/29	21
2002	5/21–5/23	36
	6/09–6/10	33
	6/22–6/23	27
	6/29–6/30	27
2003	5/03–5/04	12
	6/20–6/22	42

Administration (NOAA) and the Australian Bureau of Meteorology (Draxler, 1996, 1999; Draxler and Hess, 1998) was used to determine back trajectories of LLJ events reaching the northern Great Plains. The last date and time of a LLJ was used in the HYSPLIT model as the start time to run back trajectories. Trajectory start heights of 600, 900, 1200, 1500 and 1800 m AGL in the HYSPLIT model were used to represent possible transport heights of aphids in the atmosphere. For each trap location, origins of back trajectories were traced to 5° latitude × 5° longitude quadrant grids (from 20° to 45°N and 65° to 125°W). Across all trap locations, the proportion of LLJ duration originating from each quadrant was summed for each altitude and back trajectory time combination. Back trajectories of 12, 24, 36 and 48 h were mapped using ArcGis 8.1, developed by Environmental Systems Research Institute Inc. (ESRI). χ^2 Analysis was done in Microsoft Excel® to identify quadrants which were the most likely to be source regions for migratory aphids. Cumulative LLJ durations originating from quadrants that contributed significantly greater proportions of yearly total LLJ durations in the northern Great Plains target region were used to develop models to forecast vector abundance and spread of PLRV and PVY.

2.7. PLRV and PVY data

Data on PLRV and PVY occurrence in seed potato lots entered into the Minnesota Seed Potato Certification Program winter grow-outs in 1991–1994 and 1997–2003, was provided by the Minnesota Department of Agriculture. The proportion of seed lots in which either PLRV or PVY exceeded the 0.5% total virus threshold to reject for recertification, was used as the best available estimate of virus incidence at harvest for each crop year. North Dakota winter results were not used in this study because 2 years of winter grow-out data from that state were lost to unfavorable test conditions and because results from the two state programs may not be directly comparable.



(a)

Fig. 2. (a) Proportion of low-level jet duration of 24 h back trajectories originating from 5° latitude × 5° longitude quadrants at 600, 900, 1200, 1500 and 1800 m. Shaded area indicates Minnesota and North Dakota, USA. (b) Proportion of low-level jet duration of 36 h back trajectories originating from 5° latitude × 5° longitude quadrants at 600, 900, 1200, 1500 and 1800 m. Shaded area indicates Minnesota and North Dakota, USA. (c) Proportion of low-level jet duration of 48 h back trajectories originating from 5° latitude × 5° longitude quadrants at 600, 900, 1200, 1500 and 1800 m. Shaded area indicates Minnesota and North Dakota, USA.

2.8. Aphid prediction models

Linear regression, $y = a + bx_1$, was used to fit LLJ duration data to cumulative *M. persicae* capture across the eight trap locations through various end dates: the end of July, the first, second, third and fourth weeks of August and for the entire season (y). In this model, x_1 was cumulative LLJ duration of events originating from geographic areas that contributed significantly greater proportions (χ^2 analysis, $P < 0.05$) to total LLJ duration in northern Great Plains. Separate analyses were performed for five altitudes and four back trajectory time combinations (600–1800 m AGL, 12–48 h) and evaluated to identify which model gave the best fit. This same linear regression model was also used to fit LLJ duration to abundance of five other vector species, *M. euphorbiae*, *R. maidis*, *R. padi*, *M. avenae*, *S. graminum*, through July and the first week of August.

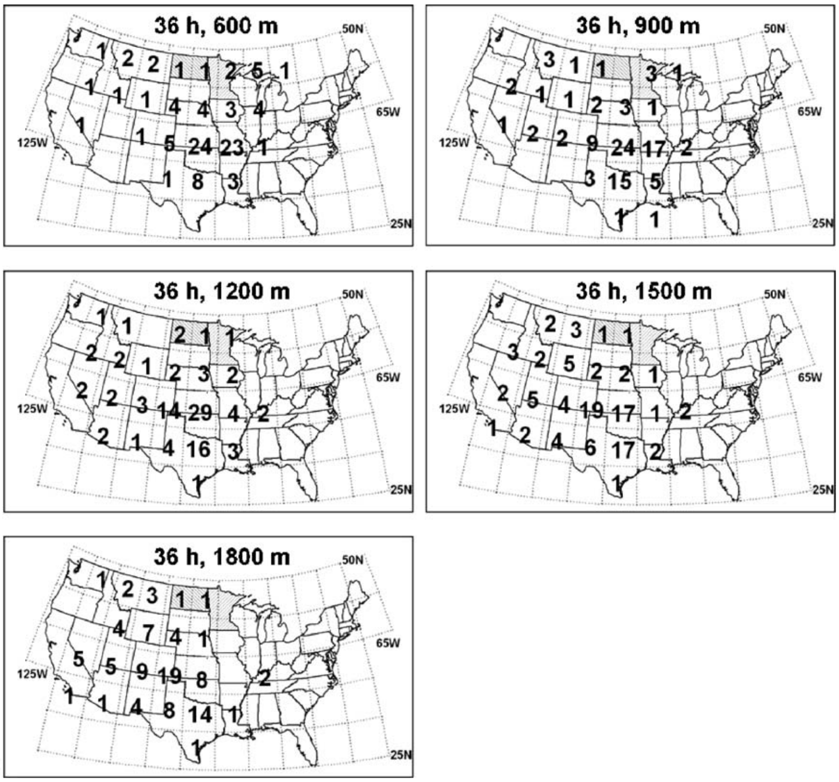
2.9. PLRV and PVY prediction models

Multiple linear regression, $y_1 = a + bx_1 + cx_2$ and $y_2 = a + bx_1 + cx_3$ was used to fit current season spread of PLRV (y_1) and PVY (y_2) to LLJ duration (x_1) and the proportion of Minnesota seed potato lots exceeding virus thresholds for recertification in the previous years seed potato crop as inoculum for PLRV (x_2) and PVY (x_3). A linear regression between the current year seed lot rejection rate and the previous year seed lot rejection rate was conducted to test the robustness of predicting current season virus spread from estimates of inoculum in the previous seed crop. Linear and multiple linear regression models were developed using XLISP-PLUS (Version 3.04) (Cook and Weisberg, 1999).

3. Results

3.1. LLJ duration

Thirty LLJ events occurred from 1 May to 30 June in 1992 to 1994 and 1998 to 2003 (Table 1). The greatest number and cumulative duration of LLJ events occurred in 1999 (8 events, 213 h) and the lowest number and duration in 1993 (2 events, 46 h). Mean across all years was 3.3 events and 94 h cumulative duration with an average duration per event of 28.2 h. Within the time period of May and June, there were eight LLJ events occurring in early May, 6 events in late



(b)

Fig. 2. (*Continued*)

May, 5 events in early June and 11 events in late June, respectively. The cumulative duration of LLJs was 416 h in May and 430 h in June across all 9 years. Within these 30 LLJ events, 23 events occurred in the night, ranging from 00 UTC (5 p.m. CST) to 12 UTC (5 a.m. CST). A preponderance of LLJ events reaching the northern Great Plains backtracked to the south central U.S. The greatest proportion of LLJ duration at 12 h back trajectories was from the area located at 35–40°N and 95–100°W at all altitudes (data not shown), whereas, the highest proportion of LLJ duration at 24 and 36 h and from 600 to 1200 m was from 30° to 35°N and 95° to 100°W (Fig. 2a), and at 1500 and 1800 m AGL was from 35° to 40°N and 100° to 105°W (Fig. 2b and c). In general, the origins of high altitude events and longer back trajectory times tended to be more scattered and further south and west than low altitude events.

Cumulative durations of LLJ events at five heights (600–1800 m) from quadrants (30–35°N, 95–100°W) were significantly greater ($P < 0.01$, χ^2 analysis) than from all other quadrants at 24, 36 and 48 h back trajectories. This region covers all or most of Arkansas, eastern Colorado, Kansas, Louisiana, Missouri, Oklahoma and northern Texas.

3.2. Rainfall

During the study period, 29 of 30 LLJ events were associated with rain from May to June in the 9 years, 1992 to 1994 and 1998 to 2003. Precipitation in most LLJ events (77%) exceeded 20 mm. Average precipitation associated with LLJ events across all locations was 17.5 mm.

3.3. Aphid capture data

Cumulative aphid captures were tallied each year across all eight trap locations, from the date of first aphid capture until each of six end dates. Absolute and relative species abundance varied greatly among years. For example, cumulative captures of *M. persicae*, across dates and locations, averaged 22.2 and 16.3 per trap in 1999 and 1998, respectively, but only 0.1 and 0.2 per trap in 1993 and 2001, respectively (Table 2). The phenology of *M. persicae* captures from the *Aphid Alert* trapping network showed few captures before the last week of July, but subsequent captures tended to remain high throughout August. *M. euphorbiae*, *R. padi*, *R. maidis*, *S. avenae* and *S. graminum* abundance also varied greatly among years (Hladilek et al., 2006).

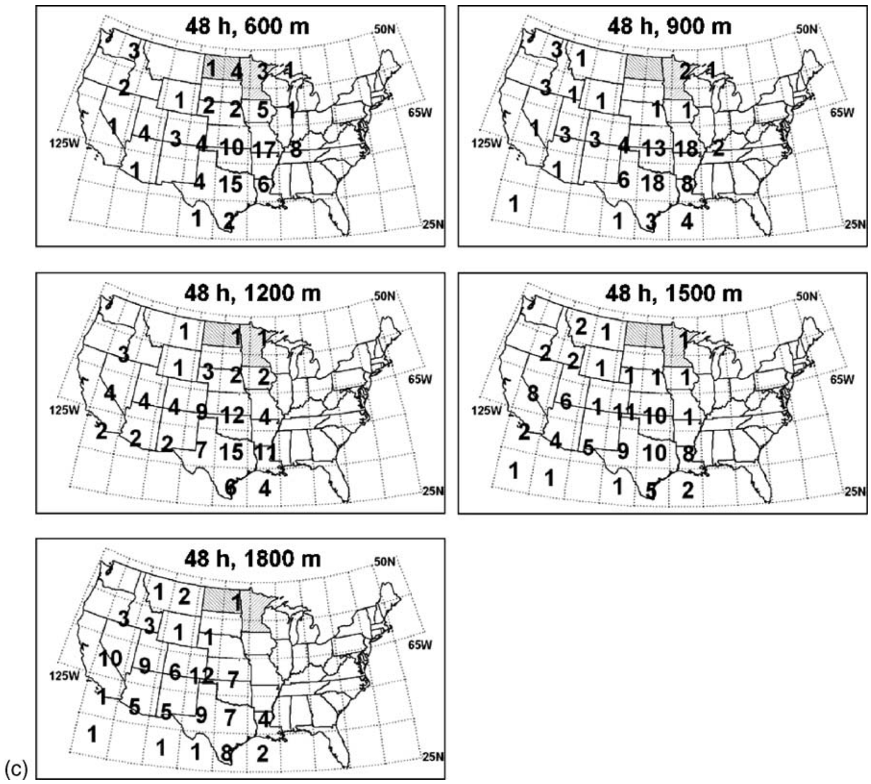


Fig. 2. (*Continued*).

Table 2
Cumulative *M. persicae* capture per trap per location through July, the first, second, third and fourth week of August and for the entire season, from eight trap locations (Baker, Climax, Karlstad and Williams in Minnesota, and Cando, Hoople, Rolette and Walhalla in North Dakota) in the northern Great Plains

Year	Cumulative aphid capture per trap					
	July	August 7	August 14	August 21	August 28	Season
1992	1.06	1.39	1.75	2.06	2.06	2.06
1993	0.00	0.03	0.03	0.03	0.13	0.13
1994	3.07	3.68	4.43	4.82	4.86	4.86
1998	0.41	1.07	4.51	7.25	12.14	16.26
1999	2.02	5.15	11.9	16.78	20.14	22.17
2000	1.26	1.48	2.70	3.11	3.28	3.37
2001	0.04	0.04	0.04	0.04	0.04	0.19
2002	0.50	1.43	2.00	2.93	4.40	4.83
2003	0.38	0.75	1.21	1.42	1.63	1.83

3.4. Virus data

The number of seed potato lots entered into the Minnesota Seed Potato Certification Program winter grow-outs ranged from 279 in 1999 to 735 in 1992 (Table 3). PLRV was epidemic from 1997 to 2000, the proportion of seed lots in which PLRV infection exceeded 0.5% ranged from 20.1% in 2000, to 40.1% in 1999. PVY was a more persistent problem than PLRV. Across all years, the proportion of seed potato lots in which PVY exceeded 0.5% ranged from 3.9% in 1993 to 52.2% in 1998 and averaged 30.9%. From 1996 through 2003, the average Minnesota seed lot rejection rate due to PVY averaged 43.1% (Table 3).

Table 3
Minnesota[a,b] potato seed lots rejected for recertification in winter grow-outs caused by virus infection exceeding tolerance levels, 1992–1994 and 1998–2003

Year	Number of seed lots entered	Proportion of seed lots exceeding threshold[b]	
		PLRV	PVY
1991	680	3.3	32.1
1992	735	2.9	19.6
1993	644	0.1	3.9
1994	588	3.2	6.5
1997	464	23.7	19.8
1998	450	31.1	52.2
1999	279	40.1	48.0
2000	418	20.1	43.1
2001	359	1.6	28.3
2002	381	0.5	39.1
2003	391	3.6	47.8

[a] Data from Minnesota Department of Agriculture, Seed Potato Certification Program.

[b] Seed potato lots in which virus infection (PLRV or PVY) exceeds 0.05%.

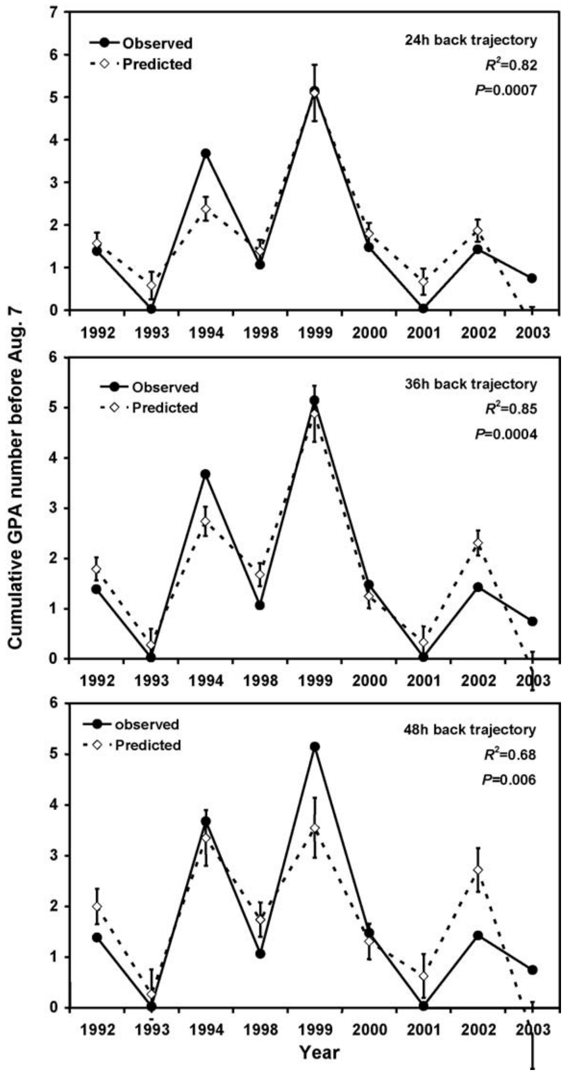


Fig. 3. Comparison of observed and predicted *Myzus persicae* capture number before first week of August in the northern Great Plains at 24, 36 and 48 backtrack hours from 1992 to 1994 and 1998 to 2003.

3.5. Aphid models

The best fit between model prediction and actual *M. persicae* captures in traps of the *Aphid Alert* trapping network was $y = -1.348 + 0.0118x$ ($R^2 = 0.85$, $P = 0.0004$). Tukey's test for non-additivity for the curvature of this model is 1.15; the *P*-value is 0.249 which indicated no significance evidence against a single linear regression model (Fig. 3). In the above equation, *y* was *M. persicae* capture through the first week of August and *x* was cumulative duration of LLJ events originating from 25° to 35°N and 90° to 105°W with 36 h back trajectories combined from 900, 1200 and 1500 m (Fig. 2b). Generally, regressions of cumulative LLJ duration and *M. persicae* capture were highly significant ($P < 0.01$) for all end dates (after July), altitudes (900–1500 m), and back trajectories (24–36 h) (Table 4). Exceptions tended to be more common for the July and late season cumulative aphid counts, altitudes of 600 and 1800 m, and back trajectories of 48 h (Zhu, 2004). Similar regression model fitting was attempted for *M. euphorbiae*, *R. padi*, *R. maidis*, *S. graminum* and *S. avenae*. However, no consistent relationships between duration of LLJ events and cumulative aphid numbers could be shown (Zhu, 2004).

3.6. Virus models

LLJ duration from May and June was used to predict current season spread of PLRV (y_1) and PVY (y_2). Linear regression between the current seasons PLRV spread and potato seed lot rejection rate in the previous winter grow-out (x_2) was significant ($R^2 = 0.588$, $P = 0.016$), but not significant for PVY (x_3, $R^2 = 0.303$, $P = 0.125$). The model providing best fit for PLRV spread was $y_1 = -10.019 + 0.0497x_1 + 0.640x_2$ ($R^2 = 0.76$, $P = 0.013$) (Fig. 4). The model providing best fit for PVY spread was $y_2 = 5.958 + 0.016x_1 + 0.691x_3$ ($R^2 = 0.37$, $P = 0.25$), where x_1 the was cumulative duration of LLJ events originating from 25° to 35°N and 90° to 105°W with 36 h back trajectories from 900, 1200 and 1500 m.

4. Discussion

Cumulative duration of LLJ events in the northern Great Plains from 1991 to 1993 and 1998 to 2003 was significantly correlated with subsequent summer capture of *M. persicae* in suction and pan traps of the *Aphid Alert* trapping network and current season spread of PLRV. A preponderance (>63%) of the spring LLJ events reaching the northern Great Plains in the 9-year period studied (1992–1994 and 1998–2003) back-tracked (24–48 h) to the south central U.S. (25–35°N, 95–105°W), an area including most or all of Arkansas, eastern Colorado, Kansas, Louisiana, Missouri, Oklahoma and northern Texas.

During this period, the average date of the last killing frost (−2.2°C) across the northern Great Plains occurred on 4 May (NCDC, 2004), thus LLJ events

Table 4
Association of *M. persicae* captures with low-level jet (LLJ) events in the northern Great Plains[a,b,c]

Wind events		R^2	P	F	$a \pm$ S.E.	$b \pm$ S.E.
Back trajectories (h)	Level (m)					
24	600	0.694	0.0050	15.89	−0.486 ± 0.634	0.030 ± 0.008
	900	0.749	0.0030	20.89	−0.867 ± 0.631	0.034 ± 0.007
	1200	0.817	0.0008	31.28	−1.048 ± 0.550	0.035 ± 0.006
	1500	0.855	0.0004	41.36	−0.872 ± 0.457	0.035 ± 0.005
	1800	0.844	0.0005	37.97	−1.136 ± 0.513	0.041 ± 0.007
36	600	0.791	0.0013	26.55	−0.888 ± 0.567	0.032 ± 0.006
	900	0.824	0.0007	32.82	−1.495 ± 0.607	0.035 ± 0.006
	1200	0.801	0.0010	28.14	−1.393 ± 0.637	0.035 ± 0.007
	1500	0.883	0.0002	52.90	−1.005 ± 0.420	0.035 ± 0.005
	1800	0.784	0.013	27.04	−0.825 ± 0.552	0.037 ± 0.007
48	600	0.674	0.0067	14.45	−0.682 ± 0.708	0.033 ± 0.009
	900	0.597	0.0147	10.36	−1.000 ± 0.913	0.034 ± 0.010
	1200	0.618	0.0120	11.31	−0.822 ± 0.829	0.034 ± 0.010
	1500	0.791	0.0013	26.44	−0.612 ± 0.522	0.037 ± 0.007
	1800	0.694	0.0053	15.90	−0.687 ± 0.678	0.046 ± 0.011

[a] *M. persicae* flight activity quantified annually, 1992–1994 and 1998–2003, as cumulative mean capture per trap in *Aphid Alert* network.
[b] Wind events quantified annually as cumulative annual duration of low-level jet (LLJ) events reaching the northern Great Plains during May and June and originating from 25° to 35°N and 90° to 105°W.
[c] Linear regression model $y = a + bx$, y = cumulative *M. persicae* capture, x = cumulative duration of low-level jet (LLJ) events in May and June.

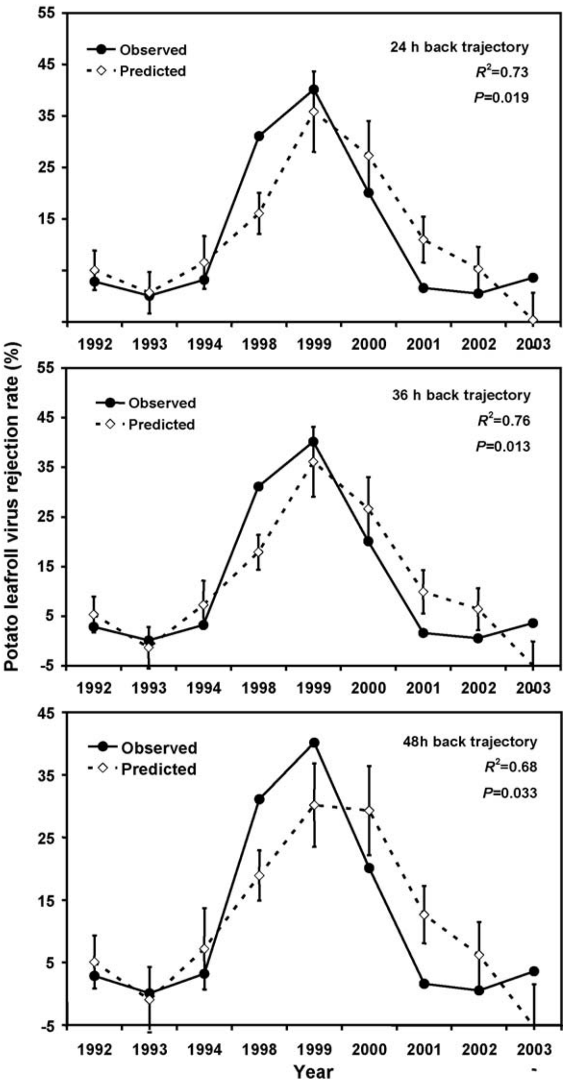


Fig. 4. Comparison of observed and predicted *Potato leafroll virus* in the northern Great Plains at 24, 36 and 48 backtrack hours from 1992 to 1994 and 1998 to 2003.

before this date probably contributed little to summer aphid populations in this area. By 1 July, local aphid populations were self-sustaining and probably more influenced by local conditions than by additional influxes of migrants from the south. Thus, cumulative LLJ duration for May and June seemed to provide the best prediction of the summer's local aphid pressure and potential for current season virus spread in the northern Great Plains.

The best correlations of LLJ duration originating from the source area (25–35°N, 95–105°W) with summer abundance of *M. persicae* or current season PLRV spread in the northern Great Plains was for back trajectories from altitudes of 900 to 1500 m AGL. Radar imaging and helicopter collection of air-borne fauna have shown that in vertical profile, aphids tend to be concentrated within various layers in the atmosphere. Thus, no single altitude trajectory can be considered as representing the migration pathway of aphids (Irwin and Thresh, 1988; Isard et al., 1990). However, trajectories under 600 m are highly influenced by surface features, and above 1800 m, air temperatures are generally too cold for aphid flight. These facts are consistent with our observation that combining trajectories from 900 to 1500 m provided best model fits.

Precipitation often terminates transport of migratory insects into the northern Great Plains. In the present study, 29 of the 30 LLJ events observed were associated with rainfall. Our data concur with the observations of others regarding the relationship of LLJs and precipitation in the Great Plains (Schubert et al., 1998; Wu and Raman, 1998). Thus, an LLJ event can not only transport small organisms long distances, e.g., tobacco blue mold, *Peronospora tabacina* D.B. Adam, cucurbit downy mildew, *Pseudoperonospora cubensis* (Berk & M.A. Curtis), and pollen, but also provides a mechanism for their deposition in the northern Great Plains (North American Plant Disease Forecasting Center, 2003).

Synoptic weather patterns during the 30 LLJ events of interest tended to have deep lows of atmospheric pressure along the Rocky Mountains and strong highs over the eastern USA. This same pattern is associated with transport of potato leafhopper, aster leafhopper, *Macrosteles fascifrons* (Stål) and *R. maidis* into the Great Plains (Carlson et al., 1992; Chiykowski and Chapman, 1965; Huff, 1963; Pienkowski and Medler, 1964; Rose et al., 1975).

The best linear regression model fit between cumulative LLJ duration and any subsequent measure of summer *M. persicae* abundance in our study was with cumulative *M. persicae* capture through the first week of August (R^2 ranging from 0.597 to 0.883 for backtrack trajectories of 24–48 h and 600–1800 m AGL). Correlations with cumulative *M. persicae* capture through 30 July and for dates after 7 August were generally statistically significant, but tended to be less robust. This may be because early season aphid captures are too few to adequately represent local population pressure while later in the season local conditions tended to have greater influence on aphid capture than the events that established the founding populations.

We do not know the extent to which long distance migrants were represented in the aerial fauna captured in the *Aphid Alert* trapping network. It seems likely that most aphids captured in the traps were actually locally produced, but for aphid species that do not overwinter in the northern Great Plains the founding populations had to be migrants. Of the vector species investigated in this study, only *M. euphorbiae* routinely overwinters in the northern Great Plains. Reproduction of this species is holocyclic (sexual) with the primary host being various species of *Rosaceae*. *M. persicae* undergoes holocyclic reproduction with the primary host being peach, *Prunus persicae* (L.), and a few closely related *Prunus* species, but continuous anholocyclic reproduction occurs in mild climates on a wide range of host plants including many agriculturally important crops. Reproduction of the other vectors of interest in this study is primarily, or exclusively, anholocyclic (asexual) lacking appropriate primary hosts and/or a suitable overwintering climate.

For anholocyclic species, extreme minimum temperature in the overwintering range may be the major factor in determining the magnitude of spring influxes of migrants to the northern Great Plains. This may explain why LLJ duration tends not to be a reliable predictor of their summer abundance in the northern Great Plains since their overwintering range and abundance varies from year to year with the annual variation in extreme minimum temperatures, closely associated with the latitudinal position and duration of the polar jet stream over North American. LLJ events are a good predictor of summer abundance of *M. persicae* suggesting that the source population of migrants of this species may be primarily holocyclic: eggs being less influenced than other life stages by extreme minimum temperatures and therefore less subject to variation in extreme minimum winter temperatures.

Prediction of current season spread of both PLRV and PVY requires not only an estimate of vector species (either direct measurement, e.g., captures of vector species, indirect measurement, e.g., LLJ duration), but also an estimate of availability of virus inoculum (e.g., results of previous years winter grow-outs from state seed potato certification programs). The relation between inoculum alone and current season spread of PLRV was significant ($R^2 = 0.588$, $P = 0.016$), and was better with two predictors, inoculum and cumulative *M. persicae* capture through the first week of August ($R^2 = 0.75$, $P = 0.015$). Models using cumulative LLJ duration as a surrogate for aphid capture data combined with the previous years Minnesota winter grow-out results provided robust estimates of current season seed lot rejection rates due to PLRV ($R^2 = 0.76$, $P = 0.013$). However, the model for the prediction of PVY using LLJ duration and PVY inoculum was considerably less reliable ($R^2 = 0.30$, $P = 0.34$) although using both *M. persicae* capture through the first week of August and PVY inoculum fit better ($R^2 = 0.39$, $P = 0.231$) than using inoculum alone to predict the current season spread of PVY ($R^2 = 0.303$, $P = 0.125$) in the northern Great Plains. This lack of fit for PVY is perhaps not surprising since LLJ duration did not reliably predict seasonal abundance of PVY vectors other than *M. persicae*. It appears that other methods will need to be developed to reliably forecast abundance of the suite of cereal aphids that are considered key vectors of PVY in the northern Great Plains (DiFonzo et al., 1997).

Difficulty in detecting PVY in certain cultivars may have contributed to the unreliability of the PVY prediction model. Potato seed lot rejection due to PVY has been exceptionally high in the northern Great Plains since the mid-1990s (average 43% from 1997 to 2003). A possible explanation for this sustained epidemic may be the popularity of certain cultivars, e.g., Russet Norkotah that are essentially asymptomtic when PVY-infected (Mollov, 2004). Recent establishment of PVY^N strains in the northern Great Plains also complicates the situation since in many cultivars PVY^N expression is mild and difficult to detect visually (Singh et al., 2003; Piche et al., 2004).

In summary, use of LLJ duration can provide a projection of current season *M. persicae* abundance approximately 1 month in advance of the usual onset of peak aphid flight activity. Analysis of weather also requires much less time and resources than operating a regional aphid trapping network. Advance prediction of aphid pressure or risk of virus spread would permit growers to modify their vector/virus management practices, e.g., in a year of low risk they might choose to delay vine kill to increase tuber yields. Predictive modeling might provide a cost effective alternative to the practice of monitoring aphid flight activity using pan traps or a costly and labor intensive regional trapping network. Unlike the use of traps, prediction models will not provide real-time information on the occurrence of local aphid flight activity. Thus, the information generated by predictive models is less useful than trap capture data in scheduling prophylactic treatments such as crop oils or insecticides. However, advance knowledge of risk might guide growers to scout their fields with appropriate intensities and to deploy tactics useful in reducing spread of aphid-transmitted potato viruses.

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