PhytoFrontiers™
An Open Access Journal from The American Phytopathological Society

Short Communication

Wind-Mediated Dispersal of Beet Leafhoppers and Pine Pollen in Southern Idaho

Carl A. Strausbaugh[1,†] | Erik J. Wenninger[2] | Laurie K. Jackson[1] | Eric Vincill[1]

[1] United States Department of Agriculture-Agricultural Research Service Northwest Irrigation and Soils Research Laboratory (USDA-ARS NWISRL), Kimberly, ID 83341

[2] Kimberly Research and Extension Center, University of Idaho, Kimberly, ID 83341

Accepted for publication 5 August 2024.

† Corresponding author: C. A. Strausbaugh; carl.strausbaugh@usda.gov

Disclaimer: Mention of trade names or commercial products in this article is solely for the purpose of providing scientific information and does not imply recommendation or endorsement by the United States Department of Agriculture (USDA). The USDA is an equal opportunity provider and employer.

Funding: The research was supported by grants from the Snake River Sugar Beet and Seed Alliance and funding for the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) CRIS project 2054-21220-006-00D.

The author(s) declare no conflict of interest.

Abstract

The management of beet leafhoppers (BLHs) is important for disease control since BLHs can vector important plant pathogens such as curly top viruses and phytoplasmas in southern Idaho. Historical data for southern Idaho suggests that BLHs need approximately 130 growing degree days (GDDs; 12.8°C base) to initiate dispersal and around 382 GDDs until they reach peak dispersal. A recent study in southern Idaho identified large peak dispersal events of BLHs on 19 May 2020 and 2 June 2021 in Elmore County near Mt. Home, ID. Historically, BLHs have been thought to originate from local areas. However, based on GDDs and dispersal numbers under optimal conditions for Mt. Home, the BLHs likely did not originate from local areas. Data for wind and pine pollen dispersal combined with GDDs for areas known to contain BLHs suggest that the BLHs could have originated outside the local area and possibly up to 142 to 515 km away. At least five conditions appear to be necessary for observation of BLH dispersal into southern Idaho: a wind event must occur (35 km/h average hourly wind speed), dispersal temperature threshold (16 to 18°C) must be met, >130 GDDs must be accumulated to initiate dispersal, daily peak temperatures should reach 24°C, and attractive BLH vegetation such as Russian thistle must be present. Combining wind event forecasts with temperature parameters in the future may make it possible to provide targeted timely insecticide sprays for BLH control.

Keywords: beet curly top, beet curly top virus, beet leafhopper, *Beta vulgaris*, *Circulifer tenellus*, common bean, *Phaseolus vulgaris*, phytoplasmas, sugar beet

The management of beet leafhoppers (BLHs; *Circulifer tenellus* Baker, synonym *Neoaliturus tenellus*; Hemiptera: Cicadellidae) is important for disease control since BLHs can vector important plant pathogens such as curly top viruses and phytoplasmas in southern Idaho (Strausbaugh et al. 2024a). The BLH can feed on hundreds of plant species, many of which can also become infected with the beet curly top virus (BCTV) (Bennett 1971; Strausbaugh et al. 2024b). Curly top has been one of the primary yield-limiting diseases in sugar beets, tomatoes, peppers, and common beans in the western United States, while BLHs carrying phytoplasmas can cause serious concerns for vegetables such as potato and stone fruit production (Bennett 1971; Cooper et al. 2023; Harper et al. 2023; Melgarejo et al. 2024; Munyaneza et al. 2008; Rojas et al. 2018; Strausbaugh et al. 2017). Disease management for BCTV centers around disease resistance and the use of insecticides to control the BLH vector (Rojas et al. 2018). However, in crops such as sugar beet, host resistance is only intermediate at best, and the neonicotinoid seed treatments used to supplement the host resistance have both environmental and regulatory concerns (Panella et al. 2014; Rojas et al. 2018; Strausbaugh et al. 2017, 2024a). Thus, host resistance needs to be improved, alternative control measures are needed, and our understanding of vector movements could be improved.

There are typically three generations of BLHs in southern Idaho (Cook 1967; Douglass et al. 1946). The female BLHs are fertilized in the fall and survive on winter annual weeds until egg laying begins in March (Douglass et al. 1946). The average duration of the egg stage can range from 5.5 days at 37.8°C to 43.8 days at 15.6°C, while the nymphal stage can take from 13.0 days at 35°C to 75.4 days at 18.3°C (Harries and Douglass 1948). Thus, the first adult generation appears in May or June, with the adults of the second generation appearing in July and early August. The adults of the third generation (overwintering generation) appear in September or October. To determine when the first generation would appear, researchers determined that 650 growing degree days (GDDs) would be necessary under controlled conditions when using a base of 14°C and a cutoff of 35°C (Harries and Douglass 1948). However, this number based on continuous temperature proved to be inadequate since the GDD summations leading to spring movement in southern Idaho were rarely more than half this amount (Harries and Douglass 1948). Thus, we chose to use numbers based on historical data for both BLH movement and climate summaries to establish GDD numbers to improve our understanding of BLH dispersal of the first generation. Therefore, this short communication was written to tie together BLH dispersal, weather data, pollen dispersal, and recently published data on BLH populations and feeding (Strausbaugh et al. 2024a, b).

Continuous BLH dispersal into crops over the field season can be expected in southern Idaho once BLHs are established in an area based on historical studies (Douglass et al. 1946). In Elmore County near Mt. Home, ID, the same continuous dispersal was observed in a recent study (Strausbaugh et al. 2024a). However, the dispersal was initiated by two large events (19 May 2020 = Week 5, and 2 June 2021 = Week 7) at the sagebrush steppe site in two consecutive years (Fig. 1) when conditions for local population development in Elmore County were suboptimal. Under optimal conditions for population development later in the season, the peak dispersals in Elmore County collected on yellow sticky cards in 1 week ranged from 58 to 69 BLHs (4 August to 1 September) at sagebrush steppe sites, 55 to 69 BLHs (4 August) at sugar beet sites, and 24 to 54 BLHs (23 June to 14 July) at dry bean sites (Strausbaugh et al. 2024a). Thus, after the initial large peaks at the sagebrush steppe sites, the BLH populations at sagebrush steppe sites and nearby crop sites were similar (Strausbaugh et al. 2024a). In a subsequent investigation into what the BLHs in Elmore County at the sagebrush steppe site had fed on prior to capture, the samples investigated from these large initial peaks appeared not to have fed recently or had just fed sparingly prior to capture, since plant DNA could not be detected in most of these samples or early season samples from other sites either (Strausbaugh et al. 2024a, b). When plant DNA could be consistently detected in BLH samples, it was in mid to late June, and the BLHs were found to have fed on pine prior to capture. These data suggest the BLH feeding on pine prior to capture had dispersed 48 to 80 km from local Idaho mountainous areas (Strausbaugh et al. 2024b). Given the temperature requirements for BLH development (the egg stage takes 5.5 days at 37.8°C to 43.8 days at 15.6°C, and the nymphal stage takes 13.0 days at 35°C to 75.4 days at 18.3°C; Harries and Douglass 1948), these BLHs that had fed on pine were likely the first BLHs to have originated in the Elmore County area both years, and the earlier large dispersals recorded where plant DNA could not be detected likely originated outside the local area. Historically, there have been reports of BLHs dispersing 320 to 482 km or more (Annand 1931; Annand and Davis 1932; Dorst and Davis 1937; Fulton and Romney 1940; Romney 1939; Severin 1933). Thus, the BLHs associated with the early season peaks at the Elmore County sagebrush steppe sites could have possibly originated a long distance away.

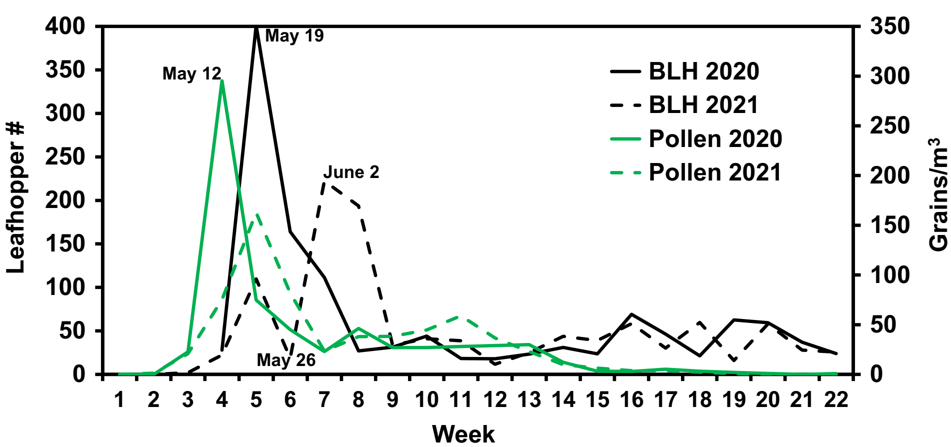

FIGURE 1

The mean number of beet leafhoppers (BLHs), *Circulifer tenellus*, at the Mt. Home, ID, sagebrush steppe site on 258 cm^2 of yellow sticky cards after 7 days and collected for 22 weeks in 2020 (solid black line) and 2021 (dashed black line) beginning 21 April. On the secondary axis, the daily average pine pollen per week collected over the same time periods by Boise Valley Asthma and Allergy Clinic in Boise, ID, which lies 64 km northwest of Mt. Home, ID. In 2020 (solid green line), the large pollen peak on Week 4 (ended 12 May) and the BLH peak Week 5 (ended 19 May) appeared to be related to the same wind event. In 2021 (dashed green line), the large pollen peak on Week 5 and the BLH peak again appear to be related to the same wind event. The BLH peak in 2021 appears to have been interrupted by cool weather on Week 6 and therefore did not peak until Week 7 (ended 2 June).

To investigate the role of wind events in possible long-distance dispersal of BLHs, pine pollen movements were assessed. Pine pollen was captured in Boise, ID (64 km from Mt. Home, ID, in Elmore County), and pollen grains captured in 2020 and 2021 mirror the BLH sampling numbers at the sagebrush steppe site early in the season (Fig. 1). Beginning 1 February, the start of pine pollen release requires 300 GDDs (12.8°C base), and peak release is at 636 GDDs (Bardon 2019). Thus, the pollen recorded in the Boise area was from out of state, since the local areas with pine such as the Wagontown RAWS station (near Pine, ID; closest station to the Elmore County BLH sagebrush steppe sample site) had only 20 to 29 GDDs by Week 5 (19 May) those same years. Peak pollen release for lodgepole pine in southern Idaho at 2,073 m occurs on 7 July, and in central and eastern Washington and Oregon at 792 to 1,295 m, peak release occurs on 13 June (Lotan and Critchfield 1990). However, peak pine pollen release for lodgepole pine at 152 m occurs on 12 May in northwestern Washington (Lotan and Critchfield 1990). The other two pine species in southern Idaho, ponderosa pine and white bark pine, have similar pollen timing as lodgepole pine (Owens and Fernando 2007; Sorensen and Miles 1974). The wind direction for the highest hourly winds on the peak pollen days was always from a northwestern direction (282 to 336°; Table 1). During Week 4 (6 to 12 May) in 2020, the wind was from a west to northwest (269 to 359°) direction 51% of the time that week. During Week 5 (13 to 19 May) in 2021, the wind was from a west to northwest (260 to 359°) direction 67% of the time that week. Thus, the data suggest the early southern Idaho pollen peaks in May likely originated in western Washington (Fig. 2).

During 1935 to 1944 in southern Idaho, the initial spring BLH dispersal ranged from 12 May to 5 June, with 25 May as the average (data from fields around Buhl and Castleford, ID; Douglass et al. 1946). The average date for peak dispersal was 24 June (Douglass et al. 1946). Based on general climate summary tables (Western Regional Climate Center, Reno, NV) for Buhl, ID (station 101217 from 1906 to 1963), the number of GDDs with a 12.8°C base reached on 24 June would be approximately 400 (Table 2). A 12.8°C base was utilized to calculate GDDs since BLH development does not occur below this temperature (Bennett 1971). For Castleford, ID (station 101551 from 1963 to 2012), the summary tables indicate that 365 GDDs would be reached on 24 June. Thus, if the summaries are averaged, in southern Idaho, BLH dispersal begins near 25 May at about 130 GDDs and peaks 24 June after approximately 382 GDDs. BLH capture data from the Elmore County sagebrush steppe site (elevation of 936 m; similar to Buhl and Castleford at 1,146 to 1,167 m) show there were two obvious peaks (Fig. 1) for BLH dispersal in a recent study (Strausbaugh et al. 2024a). The number of GDDs (12.8°C base) accumulated up to 19 May 2020 at Mt. Home (station 106174, elevation 914 m) near the collection site was only 95. Peak BLH dispersal should have occurred on 20 June 2020, since that is when Mt. Home hit 382 GDDs, which suggests the 19 May peak was from BLHs originating from outside the local area and possibly from outside the state. In 2021, BLHs peaked on 2 June when 215 GDDs had been accumulated. However, on 26 May 2021, the BLH capture number went down (Week 6 in Fig. 1) which was possibly impacted by cold weather, since daily average temperatures only ranged from 9 to 14°C. Flights of BLHs have previously been documented when temperatures reach a threshold of 16 to 18°C (Lawson et al. 1951). That temper-

TABLE 1

Four highest daily peak pine pollen grain collections in Boise, ID, in 2020 and 2021

Date	Pine pollen (grains/m^3)[a]	Highest hourly wind speed (km/h)[b]	Wind direction (degrees)[c]
6 May 2020	244	55	314
7 May 2020	372	19	310
12 May 2020	525	21	343
13 May 2020	180	19	286
13 May 2021	144	31	336
14 May 2021	150	26	324
18 May 2021	282	34	322
20 May 2021	242	45	282
Average	267	35	315

[a] Pine pollen data were collected by the Boise Valley Asthma and Allergy Clinic, Boise, ID.
[b] Wind data were collected by the Mt. Home RAWS station 102709 in Mt. Home, ID. The highest hourly wind speed recorded during each day of peak pollen collection is displayed.
[c] Wind direction was recorded during the time the highest hourly wind speed was recorded (315° indicates winds are coming from a northwest direction).

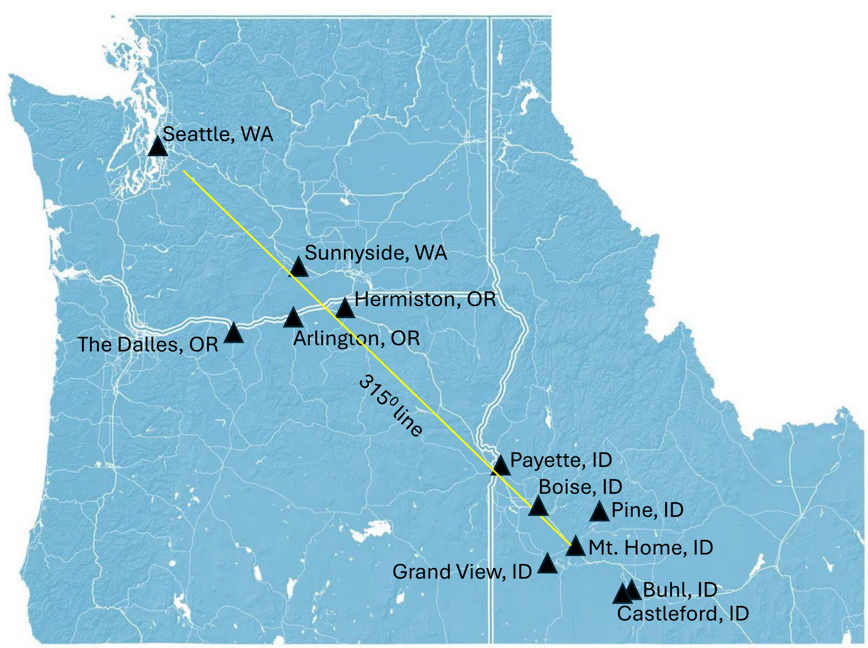

FIGURE 2

The Pacific Northwest area of the United States where beet leafhoppers (BLHs), *Circulifer tenellus*, are known to transmit curly top viruses and phytoplasmas. A recent study in the Mt. Home, ID, area indicated that BLHs may be dispersing long distances into valley areas in southern Idaho. May pine pollen data suggest that wind events carrying pollen from outside of Idaho typically come from a northwest direction (315°) and may also be carrying BLHs in the same wind events.

ature threshold was never reached during Week 6 in 2021. When BLH captures peaked in Week 7, the daily average temperatures ranged from 16 to 26°C. GDDs predicted the peak should have occurred on 14 June 2021 when over 382 GDDs were accumulated. Thus, over the 2-year period, although GDDs would have predicted the peaks to occur from 14 to 20 June, they actually occurred on 19 May 2020 and 2 June 2021, which was around the time GDDs predicted dispersal to just be starting. These observations strongly suggest that BLHs were dispersing into the Mt. Home, ID, area from outside the local area.

Despite this, the movement of BLHs into crop fields was historically thought not to be from long-distance flight but rather from local breeding grounds, including overwintering hosts like mustards in sagebrush steppe (Carter 1930; Douglass and Cook 1954; Douglass and Hallock 1957; Fox 1938; Fox et al. 1945; Haegele 1927). In both years at the Elmore County sagebrush steppe site, the sticky traps were surrounded by young Russian thistle (*Salsola* spp.) in a sagebrush steppe environment in mid-April, yet the first BLHs where the host plant could consistently be established based on plant DNA had predominantly fed on pine (Strausbaugh et al. 2024b). Thus, these data indicated that long-distance dispersal could be contributing to BLH populations in southern Idaho. The closest weather station in a forested environment to the Elmore County sagebrush steppe site is the Wagontown RAWS station 102712 (elevation 1,890 m) north of Pine, ID. The accumulated GDDs (12.8°C base) at this site in 2020 (3.5 in April, 78 in May, and 234 in June) and 2021 (8 in April, 42 in May, and 434 June) should have been sufficient to allow for BLH dispersal from surrounding forested mountainous areas located north of the Elmore County sagebrush steppe site in downslope winds in June. In both years, we also rarely detected viral and plant DNA in May BLH samples, which suggests that the BLHs had fed sparingly or not at all just prior to capture (Strausbaugh et al. 2024a, b). If the BLHs had dispersed from outside the local region (and perhaps even outside of the state) and traveled with little or no feeding, it may explain why we had difficulty detecting plant and viral DNA in May BLH samples. BLHs have been documented to be able to survive one to several days without feeding if the temperatures are low and humidity is high (Harries and Douglass 1948).

The large peaks that occurred on the cards at the Elmore County sagebrush steppe site did not occur on cards at nearby sugar beet and dry bean field sites (Strausbaugh et al. 2024a). The BLHs were likely not attracted to the dry bean sites since the fields were bare ground at that time. Dry beans are typically planted during the first week of June, while sugar beets are normally planted in early April. The small plants at the sugar beet sites could have been attractive to BLH, but the plants in these fields had a neonicotinoid seed treatment and a lot of bare ground around them. Thus, the BLHs likely did not disperse out of these fields or may not have been attracted to these sites because of bare ground. Given the long distance the BLHs possibly traveled, there was potential for peaks on sagebrush steppe site cards in Owyhee (near Grand View, ID) and Twin Falls (near Castleford, ID) counties, but the only live vegetation at these sites was sagebrush in May. The large population of young Russian thistle plants at the Elmore County sagebrush steppe site may have played a role in attracting the BLHs dispersing to this area. For many herbivorous insects in the pre-alighting stage of host habitat location, vision is more important than olfaction (Bian et al. 2020). A number of studies have shown that Cicadellidae insects have positive responses to visual cues, which implies that these leafhoppers have well-developed vision and a high sensitivity to color (Bian et al. 2014, 2020; Bullas-Appleton et al. 2004; Rodriguez-Saona et al. 2012; Shimoda and Honda 2013; Zhang et al. 2018).

In Table 2, comparing the GDDs from sites with both historical and current day data brings the impact of climate change into focus particularly when comparing historical data versus the

TABLE 2

Cumulative growing degree days with a 12.8°C base for locations in the Pacific Northwest region of the United States based on historical climate summary tables

				Cumulative growing degree days			
Location	Station number	Elevation (m)	Year[a]	March	April	May	June
Buhl, ID	101217	1,146	Historical	2	36	166	458
Castleford, ID	101551	1,167	Historical	1	26	141	421
Mt. Home, ID	106174	960	Historical	2	31	165	477
			2020	0	36	208	540
			2021	0	32	176	786
Payette, ID	106891	655	Historical	2	40	210	557
			2020	0	54	248	606
			2021	0	48	252	857
Hermiston, OR	353847	189	Historical	5	54	244	618
			2020	10	60	263	645
			2021	0	42	244	805
Arlington, OR	350265	107	Historical	7	65	289	695
			2020	0	76	288	674
			2021	0	53	277	882
Sunnyside, WA	458207	229	Historical	5	49	230	579
	458211	245	2020	0	28	153	436
			2021	0	29	168	643
The Dalles, OR	358407	30	Historical	6	59	252	611
			2020	0	52	230	537
			2021	0	39	236	757

[a] Historical = These data are from cooperative climatological data summaries available through the Western Regional Climate Center, Reno, NV. The dates covered by the historical summaries varies by site (Buhl, 1906 to 1963; Castleford, 1963 to 2012; Mt. Home, 1906 to 2007; Payette, 1892 to 2012; Hermiston, 1906 to 2012; Arlington, 1893 to 2012; The Dalles, 1893 to 2012; and Sunnyside, 1894 to 2012). The 2020 and 2021 data comes from National Oceanic and Atmospheric Administration (NOAA) weather sites and is available through the National Center for Environmental Information (https://www.ncei.noaa.gov). The Payette, Hermiston, Arlington, The Dalles, and Sunnyside locations were chosen since they lie on a line of 315° to the northwest of Mt. Home, ID, and are presented in order of increasing distance from Mt. Home. Aerial distance from Mt. Home, ID, to these locations is Payette (142 km), Hermiston (413 km), Arlington (460 km), Sunnyside (491 km), and The Dalles (515 km).

2021 GDD data for June. The June GDD data for 2021 are quite striking since the Pacific Northwest that summer experienced an unprecedented heat dome at the end of June into early July (White et al. 2023). Given that the BLH peaks recorded were not possible from local sources based on GDDs and that the wind direction during the wind events carrying pollen into the valley were from the northwest (average 315°; Table 1), areas with historical BLH populations (Cook 1967; Cooper et al. 2023; Crosslin et al. 2006; Munyaneza and Upton 2005; Munyaneza et al. 2008; Rivedal et al. 2022; Rondon et al. 2016; Strausbaugh et al. 2008; Swisher Grimm et al. 2021) that lie northwest of the Elmore County sagebrush steppe sites (Fig. 2) were considered in Table 2. Both the Mt. Home, ID (95 GDDs), and Sunnyside, WA (74), sites did not have sufficient GDDs by 19 May 2020 to initiate dispersal. The four locations mentioned in Table 2 with sufficient GDDs (>130) in May to support the initiation of dispersal were Payette, ID (144 GDDs); Hermiston, OR (164); Arlington, OR (180); and The Dalles, OR (135). In 2021, these same four areas had higher GDDs by 19 May (200 in Payette, 180 in Hermiston, 200 in Arlington, and 174 in The Dalles), but the peak did not occur until 2 June. On 2 June 2021, Mt. Home had 215 GDDs, and Sunnyside had 202, while the other locations had GDDs that were closer to the 382 GDDs necessary for peak dispersal (289 in Payette, 282 in Hermiston, 318 in Arlington, and 279 in The Dalles). Thus, not only is dispersal tied to wind events, but having warm enough weather to buildup populations and hit the threshold for dispersal must also be considered. In 2021, even though more GDDs were accumulated by 19 May, the peak that occurred on 2 June and was likely delayed by cool weather. While the wind events driving both pollen and BLH dispersal are similar in timing and magnitude in Figure 1, the pollen seems to arrive slightly ahead of the BLHs both years. In 2003, in the Columbia Basin and Yakima Valley, weedy areas around potato fields had an early peak of BLHs around 3 June, while the same areas in 2004 had a BLH population peak in mid-May (Munyaneza et al. 2008). Perhaps BLHs are dispersing from outside the state into Idaho. If BLHs can disperse 142 to 515 km, these data may also help explain why using overwintering BLH populations to predict spring populations and spraying local sagebrush steppe areas in Idaho with insecticides was unsuccessful in the past (Annand 1931; Annand and Davis 1932; Blickenstaff and Traveller 1979; Cook 1967; Dorst and Davis 1937; Fulton and Romney 1940; Romney 1939; Severin 1933). Long distance BLH migrations from the west may also explain why curly top pressure in western fields is six times higher than in eastern fields in southern Idaho (Blickenstaff and Traveller 1979).

Based on this work and previous investigations, five conditions emerge that appear to be necessary for large, long-distance dispersal of BLHs into southern Idaho: a wind event must occur (35 km/h average hourly wind speed) at the source and along the dispersal path, dispersal temperature threshold (16 to 18°C) must be met at the source (Lawson et al. 1951), >130 GDDs must be accumulated to initiate dispersal at the source, daily peak temperatures should reach 24°C at the source and along the dispersal path (Douglass et al. 1946), and attractive BLH vegetation such as Russian thistle must be present at the landing site. When these five conditions are met, southern Idaho could possibly experience a large BLH dispersal event. In the future, these conditions should be investigated to see if they can be utilized in pest alerts to warn growers that spraying is needed. In southern New Mexico, a model based on precipitation was developed to predict BLH abundance (Lehnhoff and Creamer 2020). Our observations suggest that a risk model for southern Idaho would require consideration of several environmental variables, especially those observed at putative source habitats upwind.

Currently, sugar beet growers utilize a combination of host resistance and neonicotinoid insecticide seed treatments to control the BLH vector and ultimately reduce infection of plants with BCTV (Panella et al. 2014; Rojas et al. 2018; Strausbaugh et al. 2006, 2012, 2014, 2016). However, should the neonicotinoids become compromised because of resistance buildup or become unavailable because of regulatory or environmental concerns, the low to intermediate resistance in the sugar beet cultivars would not be sufficient to avoid serious yield losses (Panella et al. 2014; Strausbaugh et al. 2016, 2017, 2024a). When the neonicotinoid seed treatments first became available, they increased sucrose yield in sugar beets by at least 15% in areas with high BCTV pressure (Panella et al. 2014; Rojas et al. 2018; Strausbaugh et al. 2006, 2012, 2014, 2016). Thus, if neonicotinoids are not available to supplement resistance, additional management measures will be necessary. Given the observations reported here, perhaps insecticide sprays could be investigated and timed in relation to wind events that facilitate BLH dispersal in May to help optimize control of BCTV in sugar beet fields in southern Idaho.

Acknowledgments

We acknowledge the Beet Sugar Development Foundation for their administrative support. We also gratefully acknowledge the technical support efforts of Anastasia Stanzak, Tamie Keeth, and Josh Reed.

Literature Cited

Annand, P. N. 1931. Beet leaf hopper's annual migrations studied in desert breeding areas. USDA Yrbk. 1931:114-116.

Annand, P. N., and Davis, E. W. 1932. Beet leaf hopper's origin important in control and in prediction of attack. USDA Yrbk. 1932:110-113.

Bardon, R. 2019. Predicting the start of the pine pollen season. North Carolina State University Forestry extension publication. https://go.ncsu.edu/readext?592038

Bennett, C. W. 1971. The Curly Top Disease of Sugarbeet and Other Plants, Monograph No. 7. American Phytopathological Society, St. Paul, MN.

Bian, L., Cai, X. M., Luo, Z. X., Li, Z. Q., and Chen, Z. M. 2020. Foliage intensity is an important cue of habitat location for *Empoasca onukii*. Insects 11:426.

Bian, L., Sun, X.-L., Luo, Z.-X., Zhang, Z.-Q., and Chen, Z.-M. 2014. Design and selection of trap color for capture of the tea leafhopper, *Empoasca vitis*, by orthogonal optimization. Entomol. Exp. Appl. 151:247-258.

Blickenstaff, C. C., and Traveller, D. 1979. Factors affecting curly top damage to sugarbeets and beans in southern Idaho, 1919-77. In: Science and Education Administration, Agricultural Reviews and Manuals, Western Series, No. 8. USDA-ARS, Oakland, CA.

Bullas-Appleton, E. S., Otis, G., Gillard, C., and Schaafsma, A. W. 2004. Potato leafhopper (Homoptera: Cicadellidae) varietal preferences in edible beans in relation to visual and olfactory cues. Environ. Entomol. 33:1381-1388.

Carter, W. 1930. Ecological studies of the beet leafhopper. USDA Tech. Bull. 206.

Cook, W. C. 1967. Life history, host plants, and migrations of the beet leafhopper in the western United States. USDA Tech. Bull. 1365.

Cooper, W. R., Walker, W. B., III, Angelella, G. M., Grimm, K. D. S., Foutz, J. J., Harper, S. J., Nottingham, L. B., Northfield, T. D., Wohleb, C. H., and Strausbaugh, C. A. 2023. Bacterial endosymbionts identified from leafhopper (Hemiptera: Cicadellidae) vectors of phytoplasmas. Environ. Entomol. 52:243-253.

Crosslin, J. M., Vandemark, G. J., and Munyaneza, J. E. 2006. Development of a real-time, quantitative PCR for detection of the Columbia Basin potato purple top phytoplasma in plants and beet leafhoppers. Plant Dis. 90:663-667.

Dorst, H. E., and Davis, E. W. 1937. Tracing long-distance movements of beet leafhopper in the desert. J. Econ. Entomol. 30:948-954.

Douglass, J. R., and Cook, W. C. 1954. The beet leafhopper. USDA Circ. 942:21.

Douglass, J. R., and Hallock, H. C. 1957. Relative importance of various host plants of the bet leafhopper in southern Idaho. USDA Tech. Bull. 1155.

Douglass, J. R., Hallock, H. C., Fox, D. E., and Hofmaster, R. N. 1946. Movements of spring-generation beet leafhoppers into beet fields of south-central Idaho. Proc. Amer. Soc. Sugar Beet Technol. 4:289-297.

Fox, D. E. 1938. Occurrence of the beet leafhopper and associated insects on secondary plant successions in southern Idaho. USDA Tech. Bull. 607:44.
Fox, D. E., Chamberlin, J. C., and Douglass, J. R. 1945. Factors affecting curly top damage to sugar beets in southern Idaho. USDA Tech. Bull. 897:29.
Fulton, R. A., and Romney, V. E. 1940. The chloroform-soluble components of beet leafhoppers as an indication of the distance they move in the spring. J. Agric. Res. 61:737-743.
Haegele, R. W. 1927. The beet leafhopper (*Eutettix tenellus* Baker): A survey in Idaho. Idaho Agr. Exp. Sta. Bull. 156:28.
Harper, S. J., Northfield, T. D., Nottingham, L. R., DuPont, S. T., Thompson, A. A., Sallato, B. V., Serban, C. F., Shires, M. K., Wright, A. A., Catron, K. A., Marshall, A. T., Molnar, C., and Cooper, W. R. 2023. Recovery plan for X-disease in stone fruit caused by '*Candidatus* Phytoplasma pruni'. Plant Health Prog. 24:258-295.
Harries, F. H., and Douglass, J. R. 1948. Bionomic studies on the beet leafhopper. Ecol. Monographs 18:45-79.
Lawson, F. R., Chamberlin, J. C., and York, G. T. 1951. Dissemination of the beet leafhopper in California. USDA Tech. Bull. 1030:59.
Lehnhoff, E., and Creamer, R. 2020. Prediction of early season beet leafhopper populations in southern New Mexico. Plant Health Prog. 21:71-76.
Lotan, J. E., and Critchfield, W. B. 1990. *Pinus contorta* Dougl. ex. Loud.: Lodgepole pine. Pages 302-315 in: Silvics of North America, Volume 1: Conifers. United States Department of Agriculture, Forest Service. Agriculture Handbook 654. R. M. Burns and B. H. Honkala, eds. USDA, Washington, DC.
Melgarejo, T. A., Cespedes, M. K., Chen, L.-F., Turini, T., Lazicki, P. A., Vinchesi-Vahl, A., and Gilbertson, R. L. 2024. Unusual outbreaks of curly top disease in processing tomato fields in northern California in 2021 and 2022 were caused by a rare strain of beet curly top virus and facilitated by extreme weather events. Virology 591:109981.
Munyaneza, J. E., Jensen, A. S., Hamm, P. B., and Upton, J. E. 2008. Seasonal occurrence and abundance of beet leafhopper in the potato growing region of Washington and Oregon Columbia Basin and Yakima Valley. Am. J. Pot. Res. 85:77-84.
Munyaneza, J. E., and Upton, J. E. 2005. Beet leafhopper (Hemiptera: Cicadellidae) settling behavior, survival, and reproduction on selected host plants. J. Econ. Entomol. 98:1824-1830.
Owens, J. N., and Fernando, D. D. 2007. Pollination and seed production in western white pine. Can. J. For. Res. 37:260-275.
Panella, L., Kaffka, S. K., Lewellen, R. T., McGrath, J. M., Metzger, M. S., and Strausbaugh, C. A. 2014. Sugarbeet. Pages 357-396 in: Yield Gains in Major U.S. Field Crops. S. Smith, B. Diers, J. Specht, and B. Carver, eds. Crop Science Society of America (CSSA) Special Publication 33. CSSA, Madison, WI.
Rivedal, H. M., Funke, C. N., and Frost, K. E. 2022. An overview of pathogens associated with biotic stresses in hemp crops in Oregon, 2019 to 2020. Plant Dis. 106:1334-1340.
Rodriguez-Saona, C. R., Byers, J. A., and Schiffhauer, D. 2012. Effect of trap color and height on captures of blunt-nosed and sharp-nosed leafhoppers (Hemiptera: Cicadellidae) and non-target arthropods in cranberry bogs. Crop Prot. 40:132-144.
Rojas, M. R., Macedo, M. A., Maliano, M. R., Soto-Aguilar, M., Souza, J. O., Briddon, R. W., Kenyon, L., Bustamante, R. F. R., Zerbini, F. M., Adkins, S., Legg, J. P., Kvarnheden, A., Wintermantel, W. M., Sudarshana, M. R., Peterschmitt, M., Lapidot, M., Martin, D. P., Moriones, E., Inoue-Nagata, A. K., and Gilbertson, R. L. 2018. World management of geminiviruses. Annu. Rev. Phytopathol. 56:637-677.
Romney, V. E. 1939. Breeding areas and economic distribution of the beet leafhopper in New Mexico, southern Colorado, and western Texas. USDA Circ. 518:14.
Rondon, S. I., Roster, M. S., Hamlin, L. L., Green, K. J., Karasev, A. V., and Crosslin, J. M. 2016. Characterization of *Beet curly top virus* strains circulating in beet leafhoppers (Hemiptera: Cicadellidae) in northeastern Oregon. Plant Dis. 100:1586-1590.
Severin, H. H. P. 1933. Field observations on the beet leafhopper, *Eutettix tenellus*, in California. Hilgardia 7:281-360.
Shimoda, M., and Honda, K.-i. 2013. Insect reactions to light and its applications to pest management. Appl. Entomol. Zool. 48:413-421.
Sorensen, F. C., and Miles, R. S. 1974. Differential frost tolerance of ponderosa and lodgepole pine megasporangiate strobili. Forest Sci. 20:377-378.
Strausbaugh, C. A., Eujayl, I. A., and Wintermantel, W. M. 2017. *Beet curly top virus* strains associated with sugar beet in Idaho, Oregon, and a western U.S. collection. Plant Dis. 101:1373-1382.
Strausbaugh, C. A., Gillen, A. M., Gallian, J. J., Camp, S., and Stander, J. R. 2006. Influence of host resistance and insecticide seed treatments on curly top in sugar beets. Plant Dis. 90:1539-1544.
Strausbaugh, C. A., Wenninger, E. J., and Eujayl, I. A. 2012. Management of severe curly top in sugar beet with insecticides. Plant Dis. 96: 1159-1164.
Strausbaugh, C. A., Wenninger, E. J., and Eujayl, I. A. 2014. Control of curly top in sugar beet with seed and foliar insecticides. Plant Dis. 98:1075-1080.
Strausbaugh, C. A., Wenninger, E. J., and Eujayl, I. A. 2016. Length of efficacy for control of curly top in sugar beet with seed and foliar insecticides. Plant Dis. 100:1364-1370.
Strausbaugh, C. A., Wenninger, E. J., Jackson, L., and Vincill, E. 2024a. Curly top viruses and phytoplasmas in sugar beets, common beans, and beet leafhoppers along with vector population dynamics in southern Idaho. PhytoFrontiers 4:305-318.
Strausbaugh, C. A., Wenninger, E. J., Jackson, L. K., and Vincill, E. 2024b. Host and shelter plants for the beet leafhopper, which vectors curly top viruses and phytoplasmas in southern Idaho. PhytoFrontiers https://doi.org/10.1094/PHYTOFR-03-24-0022-R
Strausbaugh, C. A., Wintermantel, W. M., Gillen, A. M., and Eujayl, I. A. 2008. Curly top survey in the western United States. Phytopathology 98:1212-1217.
Swisher Grimm, K. D., Crosslin, J. M., Cooper, W. R., Frost, K. E., du Toit, L. J., and Wohleb, C. H. 2021. First report of curly top of *Coriandrum sativum* caused by *Beet curly top virus* in the Columbia Basin of Washington State. Plant Dis. 105:3313.
White, R. H., Anderson, S., Booth, J. F., Braich, G., Draeger, C., Fei, C., Harley, C. D. G., Henderson, S. B., Jakob, M., Lau, C.-A., Admasu, L. M., Narinesingh, V., Rodell, C., Roocroft, E., Weinberger, K. R., and West, G. 2023. The unprecedented Pacific Northwest heatwave of June 2021. Nat. Commun. 14:727.
Zhang, X., Pengsakul, T., Tukayo, M., Yu, L., Fang, W., and Luo, D. 2018. Host-location behavior of the tea green leafhopper *Empoasca vitis* Göthe (Hemiptera: Cicadellidae): Olfactory and visual effects on their orientation. Bull. Entomol. Res. 108:423-433.