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Urban host plant utilisation by the invasive *Halyomorpha halys* (Stål) (Hemiptera, Pentatomidae) in northern Utah

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Abstract
The invasive and highly polyphagous brown marmorated stink bug, *Halyomorpha halys* (Stål), is a severe agricultural and urban nuisance pest in North America. Since its initial invasion into Utah in 2012, *H. halys* has become well established in urban and suburban locations along the western foothills of the Wasatch Front in northern Utah. Bordering the Great Basin Desert, this area is unique from other North American locations with *H. halys* due to its high elevation (> 1200 m), aridity (30-year mean RH = 53.1%; dew point = -1.9 °C) and extreme temperatures (the 30-year mean minimum and maximum in January and July in Salt Lake City range from -3.1 to 3.6 °C and 20.3 to 32.4 °C, respectively). To document which plant species harbour *H. halys*, surveys were conducted in 17 urban/suburban sites in four counties during 2017 and 2018. *Halyomorpha halys* was more abundant in Salt Lake and Utah counties than in the more northern counties of Davis and Weber and was found on 53 plant species, nine of which hosted two or more developmental stages in both years. The majority of hosts were in the families Fabaceae, Rosaceae and Sapindaceae. Northern catalpa, *Catalpa speciosa* (Warder), was the most consistent host, supporting a majority of *H. halys* detections in all life stages; thus we identify it as a sentinel host. Twenty-nine species were novel hosts for *H. halys* in North America; of these, *Acer ginnala* Maxim, *Populus tremuloides* Michx., *Prunus armeniaca* X *domestica* 'Flavor King' and *Prunus virginiana* 'Schubert' were detected with two or more life stages of *H. halys* in both years. Peak populations of *H. halys* occurred from mid-June to mid-September. We describe *H. halys* plant utilisation by life stage and seasonal period to aid future detection and management of this invasive insect in the greater Intermountain West region.

Keywords
Brown marmorated stink bug, *Catalpa speciosa*, host plant, Intermountain West, sentinel host, survey

Introduction

Native to Asia, *Halyomorpha halys* (Stål) (Hemiptera: Pentatomidae) has become an urban nuisance and severe agricultural pest in many parts of the world (Gariepy et al. 2014; Haye et al. 2015; Hoebeke and Carter 2003; Leskey et al. 2012; Macavei et al. 2015; Maistrello et al. 2016). In North America, *H. halys* has been detected in 46 U.S. States and four Canadian Provinces and observed on over 170 plant species, including a wide variety of ornamental trees, woody shrubs, vegetables, row crops and speciality fruit crops (StopBMSB.org, Haye et al. 2015). Research shows that optimal development is achieved when *H. halys* has access to multiple host species, especially those with both foliage and reproductive structures present (Acebes-Doria et al. 2016). Documentation of preferred *H. halys* hosts and plant communities is critical for studying its dispersal into novel geographic regions, such as Utah. Plant surveys for *H. halys* and other polyphagous invasive species have documented ornamental hosts and unmanaged wooded areas near suburban regions as critical for initial population establishment (Bakken et al. 2015; Branco et al. 2019). Urban and suburban areas also offer overwintering sites for *H. halys* in human-made structures, especially in areas with low winter temperatures, heavy snow accumulation and few natural overwintering sites (e.g. dead tree stands) (Lee et al. 2014).

In northern Utah, surveys in 2017 and 2018 were initiated to document plant species harbouring *H. halys* egg mass, nymph and adult life stages and their seasonal occurrence. Surveys were conducted along the urbanised western foothills of the Wasatch Front, which is considered part of the greater Rocky Mountain Range and stretches 258 km south from the Idaho border to central Utah. Approximately 80% of Utah's human population lives within 25 km of the Wasatch Range, creating a band of urban and suburban sprawl between the western mountain foothills and the eastern edge of the Great Basin Desert where much of Utah's vegetable and fruit crop production occurs (data.census.gov, nass.usda.gov). Established urban populations of *H. halys* in northern Utah present risks to speciality and field crops. For example, early season feeding by *H. halys* on tart cherry (*Prunus cerasus* 'Montmorency') fruit can invoke substantial abscission and yield loss (Schumm et al. 2020), while injury to a wide variety of vegetable and small fruit crops in urban farms reduced product quality and yields (Z. Schumm, personal communication).

The high elevation (> 1200 m), aridity (30-year mean RH = 53.1%; dew point = -1.9 °C) and extreme seasonal temperature fluctuations of northern Utah (the 30-year mean minimum and maximum in January and July in Salt Lake City range from -3.1 to 3.6 °C and 20.3 to 32.4 °C, respectively) (ncdc.noaa.gov, climate.usu.edu, worldclimate.com) present a novel environmental setting for *H. halys*. Many other regions of the world with established *H. halys* populations, especially those in North America, include more humid and lower elevation habitats (Bariselli et al. 2016; Faúndez and Rider 2017; Gariepy et al. 2014; Rice et al. 2014). Plant surveys in northern Utah will provide insights into *H. halys* invasion of other inter-mountainous regions, including identification of novel plant hosts. Documentation of primary, or sentinel, host plant species (those that support two or more life stages of *H. halys*) can aid in supporting further research and development of targeted management practices for *H. halys* (Mansfield et al. 2019).

Materials and methods

A total of 17 urban and suburban host plant survey sites were selected in 2017 and 2018, based on previous positive *H. halys* collections in Davis, Salt Lake, Utah and Weber Counties (Fig. 1). Two sites were replaced in 2018 due to lack of stink bug detections in 2017 for a total of 15 sites per year. Sites were sampled bi-weekly from 16 May to 24 August 2017 and from 8 May to 22 August 2018. In both years, a subset of six sites was surveyed until the last week of September to provide later seasonal data for sites with higher *H. halys* populations. In 2017, these six sites were numbers 3, 5, 7, 8, 9 and 10; in 2018, they were 3, 4, 7, 9, 10 and 13 (Fig. 1).

At each site, a line sampling transect, 200 m long by 40 m wide, was established. Twenty of the total available plants within each transect were randomly selected regardless of species and surveyed by one or two observers using visual inspection (e.g. underside of leaves, limbs and tree trunks) and beating sheets (BioQuip Products Inc., Rancho Dominguez, CA) for 3 min (Bakken et al. 2015). Pole pruners and a stepladder (3 m standing height) were used to examine 3–5 m height of tree canopies. For small-sized plants where all foliage could be fully inspected in less than 3 min, observers moved to the next plant upon completion. When *H. halys* was detected, plants were inspected for an additional 7 min to estimate densities of each life stage observed (egg, nymph and adult) for a total observation time of 10 min. Mean *H. halys* counts per plant species and year were calculated to provide a relevant comparison of host plant preference; however, as plant species were not equally represented in transects, the mean number of *H. halys* per visual sample is provided (Table 1). Means were not compared statistically.

Each plant surveyed within a site was assigned a unique serial number and resampled on bi-weekly visits, providing insights into seasonal phenology of *H. halys* on the representative plant species. Each surveyed plant was tracked with the mapping application Collector by Esri and data were transferred into ArcGIS Online and ArcGIS Pro for management and visualisation (Esri, Redlands, CA). Plant identifications were confirmed by the Utah State University Intermountain Herbarium (UTC), where voucher specimens of each species are archived.

Results

A total of 53 plant species from 17 families were observed with one or more *H. halys* life stages present between May and September of 2017 and 2018 (Table 1). Of these, 29 are novel hosts according to the national StopBMSB.org plant species repository.

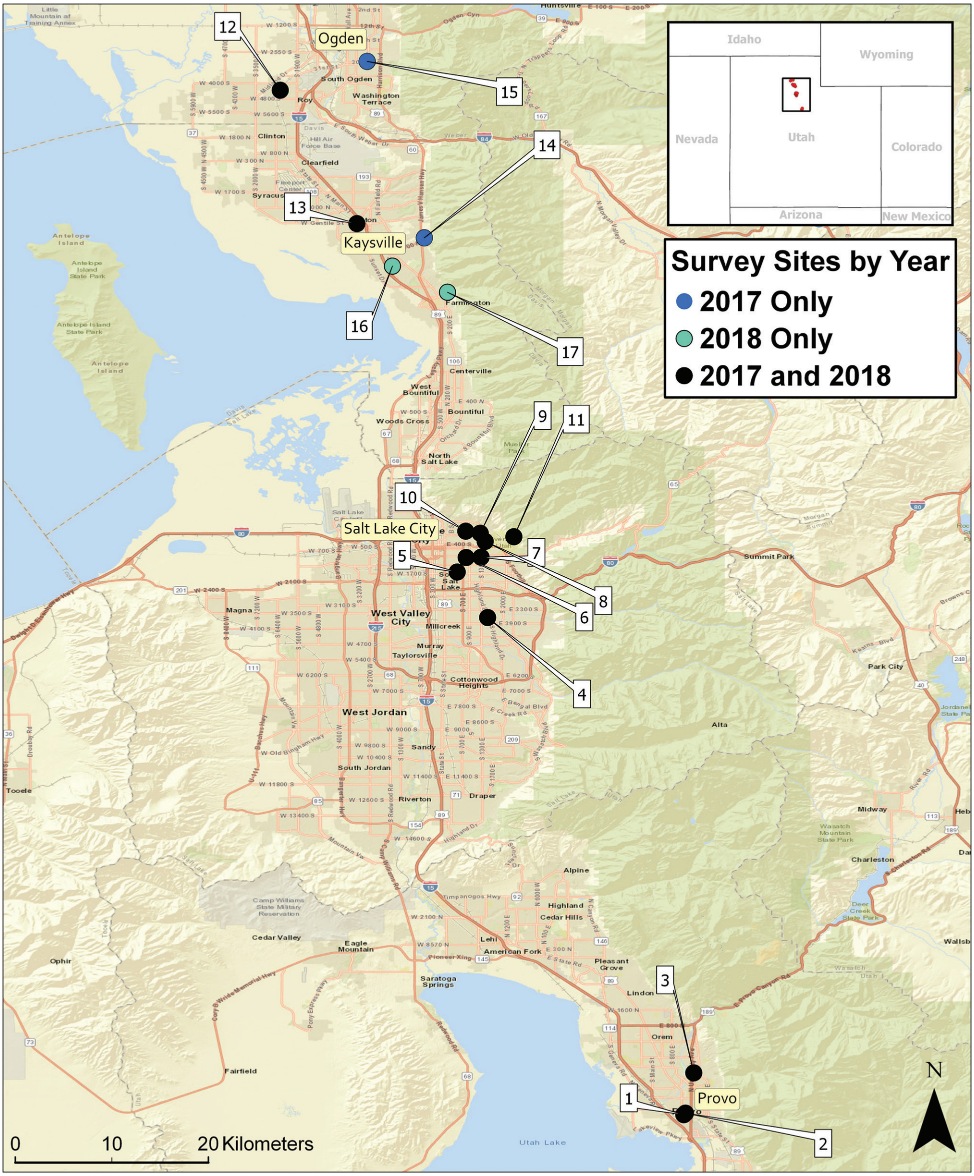

Figure 1. Map of 17 host plant survey sites in northern Utah, 2017 and 2018. Black dots represent sites that were visited in both years, blue dots represent sites visited only in 2017 and turquoise dots represent sites visited only in 2018. Geographical coordinates are as follows: Site 1: 40°13'44.7"N, 111°39'56.2"W; Site 2: 40°13'49.9"N, 111°39'50.6"W; Site 3: 40°16'05.2"N, 111°39'22.6"W; Site 4: 40°41'33.6"N, 111°50'53.8"W; Site 5: 40°44'06.4"N, 111°52'35.9"W; Site 6: 40°44'55.0"N, 111°52'05.8"W; Site 7: 40°44'56.1"N, 111°51'15.8"W; Site 8: 40°45'49.1"N, 111°51'02.1"W; Site 9: 40°46'16.5"N, 111°51'18.6"W; Site 10: 40°46'23.4"N, 111°52'07.1"W; Site 11: 40°46'04.8"N, 111°49'25.8"W; Site 12: 41°11'03.7"N, 112°02'29.2"W; Site 13: 41°03'35.9"N, 111°58'12.3"W; Site 14: 41°02'48.1"N, 111°54'26.2"W; Site 15: 41°12'40.3"N, 111°57'37.8"W; Site 16: 41°01'13.0"N, 111°56'13.1"W; and Site 17: 40°59'45.5"N, 111°53'08.5"W.

Table 1. Mean number of *H. halys* egg masses (E), nymphs (N) and adults (A) present per sample* of plant species during surveys in northern Utah, 2017 and 2018. Plant species in bold were documented with two or more *H. halys* life stages in 2017 and 2018. The number of times each plant species was surveyed (no. of unique specimens × no. of visits) is found in the column labelled (*n*). The NS term indicates no surveys were conducted on the indicated plant and year.

Family name	Scientific name	Year							
		2017				2018			
		(*n*)	E	N	A	(*n*)	E	N	A
Apocynaceae	*Vinca major*†	40	–	0.05	–	37	–	–	–
Araliaceae	*Hedera helix*†	35	–	–	0.08	32	–	0.16	–
Berberidaceae	*Mahonia repens*†	18	–	–	0.06	29	–	–	–
Bignoniaceae	*Campsis radicans*†	10	–	–	0.10	8	–	0.13	0.13
	Catalpa speciosa	284	0.05	8.81	2.70	288	0.11	7.22	0.78
Caprifoliaceae	*Lonicera maackii*†	10	–	0.20	–	10	–	0.10	–
Cornaceae	*Cornus alba* 'Elegantissima'†	10	–	0.10	0.10	10	–	–	–
Cupressaceae	*Thuja plicata*†	11	–	–	–	11	–	0.18	0.09
Fabaceae	*Caragana arborescens*	9	–	0.11	0.11	8	–	–	0.38
	Cercis canadensis	26	0.04	0.81	–	27	–	0.07	0.15
	Gleditsia triacanthos	10	–	0.10	–	10	–	0.10	–
	Gleditsia triacanthos var. *inermis*	24	–	–	–	30	–	–	0.03
	Robinia pseudoacacia	36	–	0.03	0.08	47	–	0.02	0.02
	Robinia pseudoacacia 'Purple Robe'	10	–	–	0.10	11	–	–	–
Fagaceae	*Fagus sylvatica* 'Purpurea Tricolor'†	30	0.03	0.03	0.20	30	–	–	–
	Quercus macrocarpa 'Urban Pinnacle'†	17	–	–	–	11	–	–	0.05
Malvaceae	*Tilia cordata*†	8	–	0.13	–	8	–	–	–
Oleaceae	*Forsythia* X *intermedia* 'Lynwood Gold'†	NS	NS	NS	NS	8	–	0.06	–
	Fraxinus pennsylvanica	39	–	0.03	0.05	32	–	–	0.03
	Ligustrum vulgare†	29	–	0.10	–	22	–	–	–
	Syringa vulgaris†	62	–	0.10	0.10	62	–	–	0.05
Rosaceae	*Amelanchier* X *grandiflora* †	18	–	–	–	16	–	0.06	–
	Crataegus mollis †	11	–	–	0.09	11	–	–	–
	Crataegus monogyna	8	–	0.13	0.13	8	–	–	–
	Malus domestica	55	–	0.35	0.47	53	–	0.25	0.89
	Malus floribunda†	8	–	0.13	0.75	8	–	–	0.13
	Malus 'Prairifire'†	8	–	–	0.63	8	–	–	0.13
	Malus sylvestris†	18	–	0.06	–	16	–	–	–
	***Prunus armeniaca* X *domestica* 'Flavor King'†**	28	–	0.21	0.14	22	–	0.05	0.18
	Prunus avium	35	–	0.03	0.03	29	–	0.10	–
	Prunus cerasifera	9	–	–	–	8	–	0.13	–
	Prunus cerasifera 'Nigra'	73	–	0.04	0.08	76	–	–	0.03
	Prunus domestica	11	–	–	0.55	21	–	0.71	0.05
	Prunus persica	51	–	–	–	35	–	0.11	0.17
	***Prunus virginiana* 'Schubert'†**	61	0.02	0.30	0.30	54	0.06	0.31	0.28
	Pyrus calleryana	24	–	–	–	30	–	0.03	–
	Rosa acicularis†	89	–	0.03	0.03	109	–	–	–
	Spiraea japonica 'Goldflame'†	10	–	0.30	–	10	–	0.20	–
Salicaceae	*Populus angustifolia*†	NS	NS	NS	NS	8	–	0.25	–
	***Populus tremuloides*†**	49	–	0.12	0.53	39	–	0.11	0.23
	Salix purpurea†	10	–	0.20	–	10	–	–	–
Sapindaceae	*Acer freemanii*	10	–	0.10	–	10	–	–	–
	***Acer ginnala*†**	9	–	2.78	1.78	8	–	0.25	0.13
	Acer grandidentatum†	14	0.06	–	–	16	–	–	–
	Acer negundo	78	–	–	0.03	112	–	0.02	0.06
	Acer nigrum†	8	–	0.25	0.13	NS	NS	NS	NS
	Acer palmatum 'Fireglow'	18	–	–	0.06	18	–	0.06	–
	Acer platanoides	127	–	0.26	0.06	118	–	0.03	0.04
	Acer platanoides 'Crimson King'	17	–	0.04	0.35	26	–	–	–
	Acer rubrum	8	–	–	–	8	–	0.13	–
Scrophulariaceae	*Buddleia davidii*	25	–	0.04	0.12	24	–	–	–
Ulmaceae	*Ulmus pumila*†	70	–	–	0.06	80	–	–	0.05
Vitaceae	*Vitis Vinifera*	28	–	–	–	28	–	0.04	–

*All plants were sampled for a minimum of 3 min; plants with one or more *H. halys* life stages were sampled for an additional 7 min, a total of 10 min. †Novel host plant species for *H. halys* documented in Utah (as compared to current North American literature).

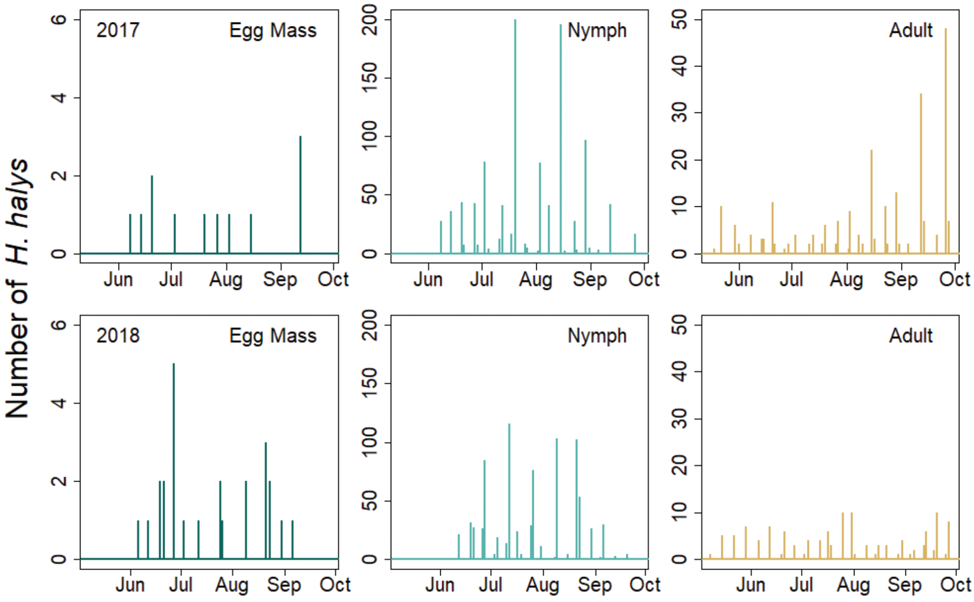

Figure 2. Total number of *H. halys* per life stage observed during plant surveys in northern Utah from May through to September, 2017 (top row) and 2018 (bottom row). Tick marks on the x-axis represent the beginning of a month. Note the unique y-axis scales for each life stage.

Seven plant species were documented with two *H. halys* life stages present across both years: *Acer ginnala* Maxim., *Acer platanoides* L., *Cercis canadensis* L., *Malus domestica* Borkh., *Populus tremuloides* Michx., *Prunus armeniaca* X *domestica* 'Flavor King' and *Robinia pseudoacacia* L. Two species, *Catalpa speciosa* (Warder) and *Prunus virginiana* 'Schubert', had all three *H. halys* life stages present in both years. The majority of *H. halys* observed were found on *C. speciosa*, comprising 91% of all *H. halys* detected in this study. Plant species without observations of *H. halys* are listed in Table 2. Additional plant species with *H. halys* detections in northern Utah, observed external to these surveys, are listed in Table 3.

Halyomorpha halys egg masses were detected in low numbers (< 40 masses) in both survey years (Table 1), with detections beginning the first week of June and continuing into early September (Fig. 2). Most egg masses were found on *C. speciosa*, followed by *P. virginiana* 'Schubert' and only single sightings on *C. canadensis*, *Fagus sylvatica* 'Purpurea Tricolor' and *Acer grandidentatum* Nutt (Table 1). Egg masses were difficult to detect due to their cryptic colouration and small size, which likely contributed to under-representation of this life stage in surveys. Nymphs were the most prevalent life stage detected and were observed between June and late September (Fig. 2). Nymphs were found on 44 of the total 53 plant species, with the highest numbers found on *C. speciosa* (Table 1). Fewer adults were detected compared to nymphs, but adults were observed throughout the entire duration of survey periods in both years, with peak detections in September 2017 (five times higher than in September 2018) and Au-

Table 2. Plant species without *H. halys* detections during surveys in northern Utah, 2017 and 2018. Surveys (*n*) indicates the number of times a species was sampled.

Family name	Scientific name	Surveys (*n*)
Adoxaceae	*Sambucus cerulea*	8
	Viburnum opulus	16
Amaryllidaceae	*Allium aflatunense*	35
Anacardiaceae	*Cotinus coggygria*	20
	Rhus typhina	7
	Rhus typhina 'Laciniata'	56
Apocynaceae	*Asclepias syriaca*	7
Asteraceae	*Artemisia tridentata*	15
Berberidaceae	*Berberis thunbergii* var. *atopurpurea* 'Rose Glow'	15
	Berberis vulgaris	21
Betulaceae	*Betula nigra*	7
	Betula papyrifera	17
Cannabaceae	*Celtis occidentalis*	15
Caprifoliaceae	*Lonicera* X *heckrottii* 'Goldflame'	17
	Symphoricarpos albus	21
Celastraceae	*Euonymus alatus*	30
	Euonymus fortunei	48
Cornaceae	*Cornus alba* 'Siberica'	24
	Cornus kousa	15
	Cornus sericea	19
Cucurbitaceae	*Cucumis sativus*	9
Cupressaceae	*Juniperus chinensis*	15
	Metasequoia glyptostroboides	16
Elaeagnaceae	*Elaeagnus angustifolia*	23
Fabaceae	*Cladrastis kentukea*	8
	Cladrastis lutea	15
	Maackia amurensis	8
Fagaceae	*Quercus gambelii*	74
	Quercus rubra	8
Ginkgoaceae	*Ginkgo biloba*	21
Grossulariaceae	*Ribes alpinum*	21
Hydrangeaceae	*Philadelphia* X *virginalis*	8
Juglandaceae	*Juglans regia*	53
Lamiaceae	*Nepeta cataria*	16
Lauraceae	*Lindera benzoin*	15
Magnoliaceae	*Liriodendron tulipifera*	21
	Magnolia denudata	15
Malvaceae	*Alcea rugosa*	56
	Hibiscus syriacus	7
	Tilia platyphyllos	16
	Tilia tomentosa	8
Oleaceae	*Forsythia* X 'Northern Sun'	8
	Syringa 'Bailbelle'	8
	Syringa reticulata 'Ivory Silk'	8
	Syringa vulgaris 'Ludwig Spaeth'	8
	Syringa X *hyacintriflora*	15
Plantaginaceae	*Penstemon strictus*	16
Rosaceae	*Crataegus crus-galli* var. *inermis*	16
	Crataegus laevigata 'Paul's Scarlet'	14
	Crataegus X *lavellei*	16
	Fragaria vesca	15
	Malus ioensis	33
	Physocarpus opulifolius 'Dart's Gold'	23
	Physocarpus opulifolius 'Diablo'	8
	Prunus americana	8
	Prunus dulcis	14

Family name	Scientific name	Surveys (*n*)
Rosaceae	*Prunus mahaleb*	16
	Prunus X *cistena*	19
	Pyrus pyrifolia	7
	Rosa spp.	168
Rosaceae	*Prunus virginiana*	59
	Sorbus alnifolia	8
Rutaceae	*Tetradium daniellii*	8
Salicaceae	*Populus deltoides*	7
	Salix lasiolepis	8
Sapindaceae	*Acer campestre*	18
	Acer griseum	21
	Acer saccharinum	7
	Aesculus hippocastanum	16
	Aesculus X *carnea* 'Briotii'	8
	Koelreuteria paniculata	8
Saxifragaceae	*Astilbe* X *arendsii* 'White Gloria'	17
Simaroubaceae	*Ailanthus altissma*	40
Solanaceae	*Capsicum annuum* 'Big Bertha'	9
	Lycium barbarum	19
	Solanum melongena	25
Ulmaceae	*Ulmus americana* 'Lewis & Clark'	8
	Ulmus parvifolia 'Emer II'	8
	Ulmus propinqua 'Emerald Sunshine'	8
Vitaceae	*Parthenocissus quinquefolia*	66

Table 3. Additional *H. halys* host plant species documented in northern Utah, but extramural to the surveys in this study, 2017–2020.

Family name	Scientific name
Asteraceae	*Helianthus annuus*
Boraginaceae	*Borago officinalis*
Cucurbitaceae	*Cucurbita pepo*
Fabaceae	*Phaseolus vulgaris*
Lamiaceae	*Ocimum basilicum*
Moraceae	*Morus alba*
Poaceae	*Zea mays*
	Zea mays 'Everta'
Rosaceae	*Prunus armeniaca*
	Prunus cerasus
	Prunus persica
	Pyrus communis 'Williams'
	Rubus idaeus
Salicaceae	*Populus fremontii*
Solanaceae	*Solanum lycopersicum*

gust and September 2018 (Fig. 2). Adults were found on 36 plant species, most commonly on *C. speciosa*, with sporadic high density sightings on several species within the families Rosaceae and Sapindaceae, specifically those within the genera *Acer* and *Malus* (Table 1). Total numbers of nymphs and adults detected were nearly 1.5 times greater in 2017 than in 2018 (3,611 in 2017 and 2,515 in 2018) (Figs 2, 3).

In general, sites surveyed in Salt Lake and Utah Counties had higher densities of *H. halys* in both years than sites in Weber and Davis Counties to the north (Fig. 3). The site containing the highest densities of *H. halys* was in the Avenues neighbourhood (Site 9) of Salt Lake City. This area contains street blocks lined with large, mature ornamental trees and is within 3 km of the University of Utah campus where *H. halys* was

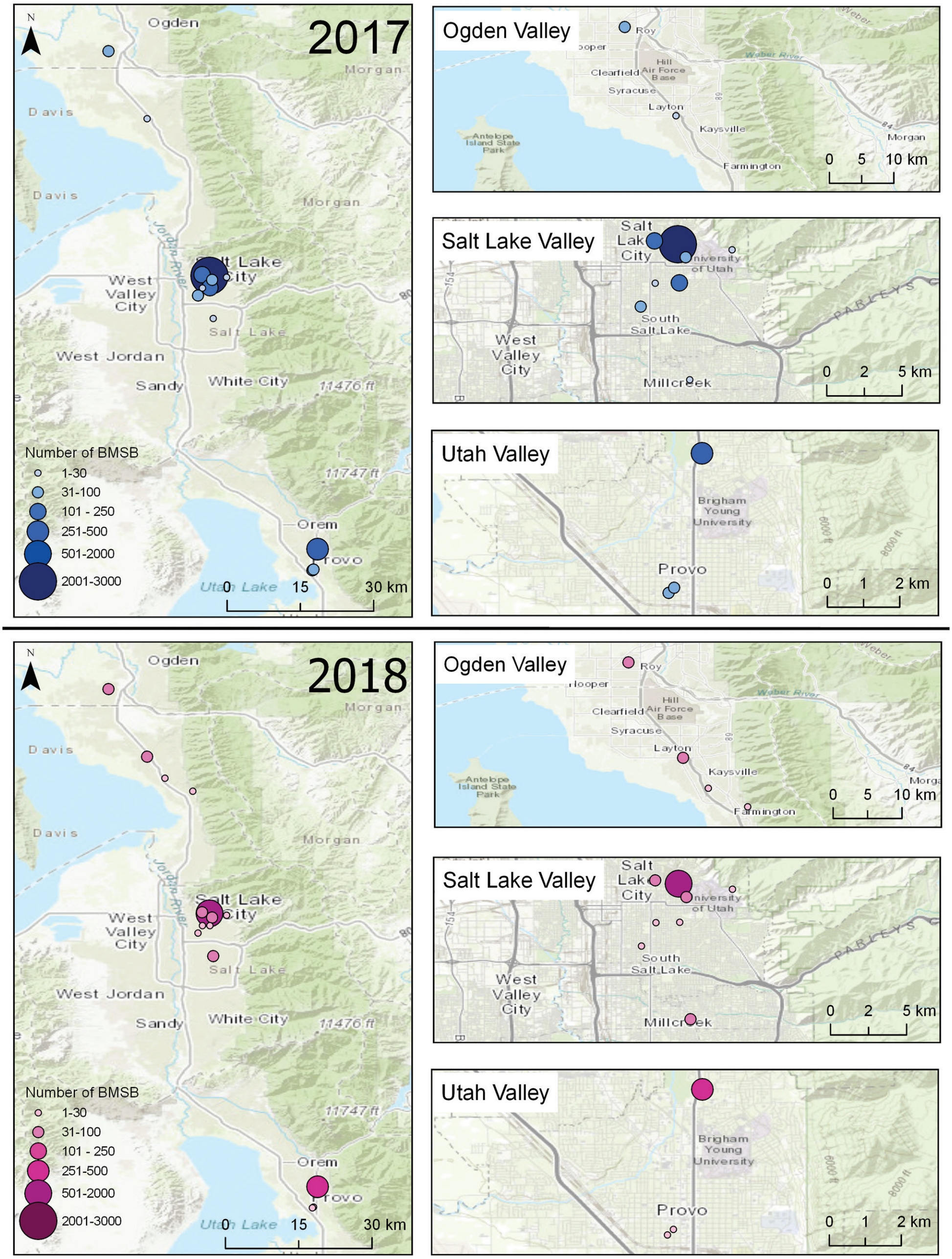

Figure 3. The total number of *H. halys* detected at survey sites in 2017 (top left) and 2018 (bottom left). The maps on the right show magnified views of Ogden Valley (Weber and Davis counties), Salt Lake Valley (Salt Lake County) and Utah Valley (Utah County).

originally detected in Utah in 2012. Site 3 in northern Provo, Utah County, had the second highest density of *H. halys* sightings. Both locations were next to large apartment buildings with several *C. speciosa* trees in close proximity.

Discussion

Surveys in northern Utah for *H. halys* have documented several prominent host plant species belonging to the families Bignoniaceae, Fabaceae, Rosaceae and Sapindaceae. These families, along with their most commonly encountered genera (*Catalapa*, *Cercis*, *Malus*, *Prunus* and *Acer*), have been documented as beneficial hosts for *H. halys* in other regions of North America (Hoebeke and Carter 2003; Bakken et al. 2015; Bergmann et al. 2016) and Asia (Lee et al. 2013). Twenty-nine of the plant species observed in this northern Utah study were novel *H. halys* host detections for North America (StopBMSB.org). Some novel hosts, such as the native *P. tremuloides*, supported both nymph and adult *H. halys* on the bark and foliage. No direct observation of feeding or plant damage was recorded; however, *P. tremuloides* may be an important host for *H. halys* establishment in Utah as it is a commonly planted ornamental tree and known to sustain biodiversity, native habitat and other ecosystem services in the intermountain region (Rogers et al. 2020). Our surveys were only conducted in urban areas; therefore, further study is needed to confirm the potential for wild *P. tremuloides* to support *H. halys*, including other intermountain areas where this tree is an important native plant.

Acer ginnala was a novel host with consistent nymph and adult detections in both survey years, especially from May to June. This early season preference could be due to nutrient availability and plant health, as many *A. ginnala* experience foliar chlorosis in mid to late summer due to a lack of iron from alkaline soils in Utah (Mengel 1994), possibly making this host less desirable in the mid and later season. The only host species, besides *C. speciosa* to exhibit all three life stages of *H. halys*, was *P. virginiana* 'Schubert', which is also a novel host species. This association is likely due to its large plantings in northern Utah residential areas, attractive fruiting structures for feeding and dense protective canopy. This species is also exploited by several native stink bug species, specifically *Chinavia hilaris* (Say). However, the Utah native *P. virginiana*, did not host *H. halys* during these surveys, suggesting the ornamental *P. virginiana* 'Schubert' is a more suitable host, possibly because it offers a larger canopy and is more common near *H. halys* overwintering sites, such as human-made structures. More extensive sampling of the native *P. virginiana* is suggested to support a more comprehensive comparison.

The most common and consistent host plant for *H. halys* in northern Utah is the northern catalpa, *C. speciosa*; the highest number of egg masses, nymphs and adults were found on this host in both survey years. Our observations support other surveys in North America and Eurasia where *H. halys* was common on *C. speciosa* (Bakken et al. 2015; Musolin et al. 2018). Resources of this plant that seem to attract *H. halys* are its large leaves, flowers and reproductive pod structures. The undersides of the large leaves are especially advantageous for *H. halys* oviposition. As a primary and sentinel host, *C. speciosa* is a target for prevention, detection and management practices against the spread and further establishment of *H. halys* into agricultural lands in Utah. Contrary to other reports in North America that document *Ailanthus altissima* (Mill.) Swingle as a prominent host plant (Rice et al. 2014; Bakken et al. 2015; Bergmann et al. 2016), our surveys of this species (sampled 40 times in 2018 only, Table 2) did not detect *H. halys*. We project that the host status of *A. altissima* could change in Utah given its apparent preference by *H. halys* in other regions of North America.

The occurrence and abundance of certain plant species impacted the survey results, as stated for *P. virginiana* 'Schubert' above. This is largely due to *H. halys* quickly dispersing by flight (Wiman et al. 2015) and using plants for a variety of functions (Bergmann et al. 2016), including resting between flights. Therefore, it is reasonable to assume that more abundant plant species in an urban landscape are more likely to harbour dispersing adults. *Acer plantanoides* was a major component of urban vegetation cover in all of the surveyed counties in northern Utah, likely contributing to some of its observed *H. halys* abundance. A similar association can likely be applied to common ornamental plant species in families Fabaceae, Rosaceae and Sapindaceae. We did observe some exceptions; a notable one being the genus *Rosa*, with few *H. halys* detections.

Although *H. halys* has been detected on plants, in pheromone traps and by the public in multiple locations in Utah, established populations are primarily concentrated along the Wasatch Front (west side of the Rocky Mountain range). To date, the highest densities of *H. halys* reside within Salt Lake and Utah Counties. The concentration of *H. halys* in the larger metropolitan areas of Salt Lake and Utah Counties is most likely due to its original detection and establishment in Salt Lake City with expansion into nearby urban centres. These urban areas offer overwintering shelter in human structures (Lee et al. 2014), wooded areas with mature ornamental hosts (Bakken et al. 2015) and human-mediated vectors of transport (e.g. Interstate 15, Union Pacific Railroad) (Wallner et al. 2014). Urban centres with high populations of *H. halys* are in close proximity to northern Utah's agricultural production areas, especially speciality fruit and vegetable crops which are at risk of feeding damage by *H. halys* (Schumm 2020; Schumm et al. 2020). Identification of ornamental plants that harbour *H. halys* in the urban-agricultural interface is critical for providing information for preventative management decisions and for better management of future crop invasions.

Using *C. speciosa* and other prominent host plants identified in this study as sentinel hosts, property owners and land managers in Utah, as well as other surrounding States in the greater Intermountain West, can more accurately track the invasion and establishment by *H. halys* (Mansfield et al. 2019). Beyond host plant species data, these surveys provide a temporal context for *H. halys* development across its multiple life stages in northern Utah. Nymphs were observed in significantly higher numbers than egg masses and adults from mid-June through to early September. This suggests that Utah growers and land managers should initiate monitoring using beat sheets or traps in May or early June, with treatment needs assessed from June through to September with consideration of crop and harvest timelines.

Interestingly, overall populations of *H. halys* nymphs and adults decreased from 2017 to 2018. The reason for this population decline is unknown. No major differences in relative humidity, temperature and cumulative degree-days occurred between the two survey years when utilizing the predictive phenology model of Nielsen et al. (2008, 2016). For example, in Salt Lake City where the majority of sites were located, the mean minimum/maximum temperatures and minimum relative humidity in May of 2017 and 2018 were 7.7/21.9 °C and 24.4% and 9.3/23.6 °C and 24.2%, respectively. In September 2017 and 2018, the mean minimum/maximum temperatures and minimum relative humidity was 10.2/24 °C and 29.7% and 11.2/28.6 °C and 13.6%, respectively (climate.usu.edu). Temperatures and relative humidity were more similar between years in the June through to August survey periods and fell between environmental conditions observed in May and September. Regardless, *H. halys* populations are still relatively low in Utah compared to other regions of North America where climate conditions are more favourable for *H. halys* (Rice et al. 2014; Nielsen et al. 2016). Extreme high temperature and low humidity are known to negatively affect *H. halys* survival and reproduction (Nielsen et al. 2008; Haye et al. 2014; Fisher et al. 2020).

Another limiting factor could be egg mortality by parasitoid wasps. *Trissolcus japonicus* Ashmead, a parasitoid of *H. halys* native to its home range, was first detected in Utah in Salt Lake City in June 2019 and expanded its abundance and range in 2020 (Holthouse et al. 2020; K. Richardson, personal communication). However, egg mass parasitism rates by native wasps in northern Utah surveys were similar between 2017 and 2018 and *T. japonicus* was found only after these host plant surveys were conducted. Another organism that may have caused this population decrease is *Nosema maddoxi* Becnel, Solter, Hajek, Huang, Sanscrainte and Estep (Hajek et al. 2017). This microsporidian is known to cause mortality in *H. halys* adults and nymphs and was detected in wild-caught *H. halys* specimens in Salt Lake City and Provo, Utah in 2017 (Preston et al. 2020; C. Preston, personal communication). However, in 2018, dissections of 141 adult *H. halys*, collected from several locations in Salt Lake City and Provo, Utah, revealed no *N. maddoxi* spores, implying the microsporidian was absent or collection/dissection methods were ineffective in detecting its presence (M. Holthouse, unpublished data). Despite our inability to explicitly define a cause for declines in *H. halys* populations along the Wasatch Front since 2017, this trend has continued into 2020 (M. Holthouse, unpublished data).

Conclusion

Plant surveys for the invasive brown marmorated stink bug, *H. halys*, within the urban landscape of northern Utah, have revealed 53 host plant species from 17 families capable of harbouring one or more developmental life stages of the insect. Of these plant species, *C. speciosa*, northern catalpa, harboured the predominance of *H. halys* eggs, nymphs and adults across survey sites and years. Peak numbers of *H. halys* nymphs, the most abundant life stage, occurred between June and early September in both years with highest densities in Salt Lake and Utah Counties. A notable novel host is *P. tremuloides*, an important native tree in the Intermountain West and other interior western regions. We documented that *H. halys* can be found season-long on a wide variety of managed ornamental plants and identified 29 novel host species in northern Utah.

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