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Seasonal Dynamics of the Brown Marmorated Stink Bug, *Halyomorpha halys* (Hemiptera: Pentatomidae), in Apple Orchards of Western Slovenia Using Two Trap Types

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Abstract: The invasive *Halyomorpha halys* is a serious pest for several fruit trees, causing millions of dollars of crop damage every year across the world's major fruit-growing regions. Once established in an orchard, *H. halys* quickly becomes the predominant stink bug species and is a major season-long pest. Annual increases in the population size of *H. halys* have resulted in increased pest pressure and a growing risk of severe crop damage. Reliable monitoring is indispensable for *H. halys* control and management, providing comprehensive information on the seasonality of pest population dynamics, abundance, and interaction with the environment, and is essential for the successful implementation of integrated pest management (IPM) strategies to prevent crop damage. Our study followed the seasonal population dynamics of *H. halys* in three apple orchards in the Goriška region of western Slovenia over the period 2019–2021. Pherocon® Dual Panel Adhesive Traps (Trece Inc.) and pyramidal Rescue® Stink Bug Traps, both baited with Trécé lures (two-component *H. halys* aggregation pheromone + pheromone synergist), were used to monitor *H. halys* adults and nymphs weekly from late March to the end of November. Captures taken with both types of trap clearly describe the seasonal dynamics of *H. halys*, with the first occurrence of overwintering adults in April and May, and with two peak occurrences in adults, in the middle of summer and in the beginning of autumn, corresponding to the appearance of two generations per year in the study area. The growing trap captures observed during the 3-year monitoring period suggest that *H. halys* was only recently introduced to the area and that natural enemies have not yet been fully recruited. Pyramid traps captured significantly more adults and nymphs than clear sticky traps and provided accurate monitoring of *H. halys* life stages throughout the season. Regardless of the lower trap catches of adults and juveniles, clear sticky traps clearly displayed *H. halys* seasonal dynamics pattern. Therefore, their use is recommended as an early detection tool in areas where pests are not yet present, or in areas with small *H. halys* populations. *Halyomorpha halys* adult trap captures were higher in Šempeter orchards, within areas of great landscape diversity and a large share of urban land. The seasonal dynamics of *H. halys* over the 3-year period were closely related to weather conditions, with temperature and relative humidity as the major factors affecting population growth.

Keywords: *Halyomorpha halys*; invasive species; population dynamics; landscape diversity; pheromone trap

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1. Introduction

Invasive alien species are inevitable negative side effects of the increasing globalization in trade and transport and pose a continuous threat to biodiversity, human health and the economy [1,2].

Multiple accidental introductions of *H. halys* in North America [3,4] and Europe [5–7] were followed by rapid spreading across the Northern Hemisphere, with a strong tendency to expand southwards. Recently invaded areas also include Eurasia, South America and North Africa [8–10]. As a stowaway in passenger luggage and imported bulk freight, cargo and vehicles [11], it has been intercepted several times in Australia and New Zealand, but has not yet been established [12,13].

Halyomorpha halys has emerged in recent decades as a major pest of fruits and vegetables of worldwide importance, causing millions of dollars of crop damage annually, and huge controlling costs [14–18]. *Halyomorpha halys* is among the most difficult insect pests to control because of its high landscape mobility and polyphagous feeding behaviour, allowing it to swiftly colonize new areas [19]. Even unnoticeable populations present in tree fruits may cause significant crop damage [20].

Managing this invasive alien species is particularly challenging in the first period after a mass outbreak [21]. The lack of basic biological knowledge of *H. halys* and its behaviour in a new environment, information on natural enemies in invaded areas, and the absence of other effective control measures, such as exclusion nets [22], has left farmers with few options for pest control and has resulted in the need for immediate insecticide-based management programs [14].

There is now extensive experience in *H. halys* control at the global level, with repeated use of insecticides being the most commonly used tactic against this harmful pest. Due to the aforementioned reasons, insecticide use has considerably increased in fruit plantations, which can conflict with the already established integrated pest management programs for perennial crops [16,23,24]. During the initial invasion, in the absence of reliable monitoring and decision-making tools, farmers mostly rely on calendar-based insecticide sprays for *H. halys* [25].

Reliable monitoring of the pest population is a key element of integrated pest management [26]. Particularly when dealing with an invasive alien species like *H. halys*, monitoring is essential to obtain a better understanding of its behaviour and ecology in the newly invaded area, providing detailed information on pest population size and distribution over time and space, and is indispensable for developing effective management strategies [23,27].

Trapping systems for insects are important components of integrated pest management programs. Trapping data are used to support management decisions like insecticide application timing based on thresholds, as well as to assess the efficacy of all control measures that have been implemented [28].

The discovery of the two-component aggregation pheromone [29] and the pheromone synergist [30] formed the basis of different types of traps that we recently developed and experimentally tested [25,31–35]. In trap comparison studies, *H. halys* most often strongly responded to ground-deployed black pyramid traps baited with pheromone lures [36], making this trap a standard decision support tool in apple orchards [37]. Pheromone-baited black pyramid traps captured more *H. halys* than all other types of traps, and provided effective season-long monitoring of *H. halys* adults and nymphs. However, they also have some downsides that need to be considered prior to implementation. Standard black pyramid traps are costlier compared to others, time-consuming to deploy and service and (due to their size) require a large space, making them not best suited for growers' needs [33].

Different alternative trap designs and deployment strategies were developed and tested recently, e.g., a modified jar top pyramid, a pipe trap, a small black plastic pyramid (ground and canopy deployed), a small hanging pyramid and a delta trap [32,33,38] in order to find a simpler, less expensive and suitable replacement for the standard black pyramid trap.

Landscape characteristics, such as landscape diversity, patch size and fragmentation, have an important impact on the insect pest dispersal capacity, pest population dynamics and size [39]. As landscape patterns in agroecosystems can vary in space and time, this can be reflected by altered distribution and pest abundance [40]. In recent years, many studies have contributed to a better understanding of the *H. halys* biology and ecology [41–45], its natural enemies and its movement between different crops, landscapes and adjacent habitats [46–48], which has led to the development of behaviour-based integrated pest management (IPM) tactics [49].

The natural spread and movement patterns of *H. halys* at landscape levels are closely related to its host preference, including wild and cultivated crops throughout the season [50,51]. Host plant availability and distance from source populations, landscape features and land use also play an important role in pest distribution [46]. An important contribution in maintaining populations of *H. halys* is likely made by non-crop hosts growing in the habitats that surround fruit orchards [27].

Furthermore, population abundance and pest pressure are affected by climatic conditions, with temperature and humidity as the most influential factors [52,53]. Knowledge of the interactions between climate, resource availability and propagule pressure can help estimate the pest potential of *H. halys* and the vulnerability of agricultural systems in endangered regions [54]. According to Rice et al. [36], the local climate and vegetation play a key role in the build-up of the *H. halys* population, which increases the risk of crop damage.

Despite the large amount of research on this issue, long-term studies addressing the behaviour of *H. halys* within specific habitats and landscapes are still needed. Linking biological patterns of pests with environmental variability could provide valuable information to upgrade IPM programs for endangered crops.

Halyomorpha halys (Stål, 1855) (Hemiptera, Pentatomidae), a stink bug native to East Asia, may be used as a model organism to better understand the concepts of uncontrolled introduction, rapid expansion and disruptive potential of invasive insects and their environmental, economic and social impacts on society.

Our study was carried out in a focal area of *H. halys* invasion within Slovenia in the Goriška region (Western Slovenia). First found in 2017 [55], it expanded its range to other parts of the country, becoming an important pest of fruits and vegetables and a major nuisance in urban areas [56]. The Goriška region is characterized by high landscape diversity and land use fragmentation. Consequently, the agricultural production diversity in the area is very high, with small-scale farms predominating production systems. Peaches and pears are the dominant fruits in the region, followed by apples, cherries, apricots and plums. Viticulture, row crops (maize, potato sunflower and alfalfa) and vegetable crops also represent an important share and complement the diversity of regional agricultural production.

The main objective of this study was to monitor the seasonal dynamics of *H. halys* in apple orchards at three different locations in Western Slovenia over a three-year period. As a secondary objective, the efficacy of two types of commercially available traps, characterized by simpler use and a lower price, were evaluated, and their suitability for practical use is discussed.

2. Material and Methods

2.1. Study Area

Seasonal abundance and population dynamics of *H. halys* were studied over three years (2019–2021) in the Goriška region of western Slovenia. Weekly monitoring of *Halyomorpha halys* was conducted from the end of March to the end of November each year in three commercial apple orchards (between 0.5 and 1.0 ha), located approximately 5.0–6.0 km apart (Table 1). The introduction of *H. halys* occurred at the same time in all locations, and the first appearance was recorded in 2017 [55].

2.2. Weather Data

Meteorological data were obtained from the agrometeorological weather station Bilje/Nova Gorica (45°53′44.05″, 13°37′26.65″), which was centrally located, almost equidistant, approximately 5 km from each individual orchard involved in the study. Hourly measurements of temperature, rainfall and relative humidity were summarized as monthly and weekly averages (temperature and humidity) and sums (precipitation) (Figure 1).

Table 1. Data on trapping locations.

Location No./Name	GPS Coordinates	Elevation (m)	Orchard Size (ha)	Main Characteristics of the Surrounding Landscape
Location 1 Šempeter pri Gorici	45°55′55.3908″ N 13°38′42.6408″ E	84.0	0.5 ha	Urban area (extensive orchards and vineyards, ornamental plants, trees and bushes, overgrown farmland and forest)
Location 2 Dombrava	45°53′41.406″ N 13°40′54.3144″ E	49.0	1.0 ha	Intensive agricultural area (intensive fruit plantations, vineyards and row crops)
Location 3 Miren	45°53′20.5116″ N 13°35′37.7916″ E	40.0	1.0 ha	Extensive agricultural area (permanent grassland, row crops, overgrown farmland, forest and water)

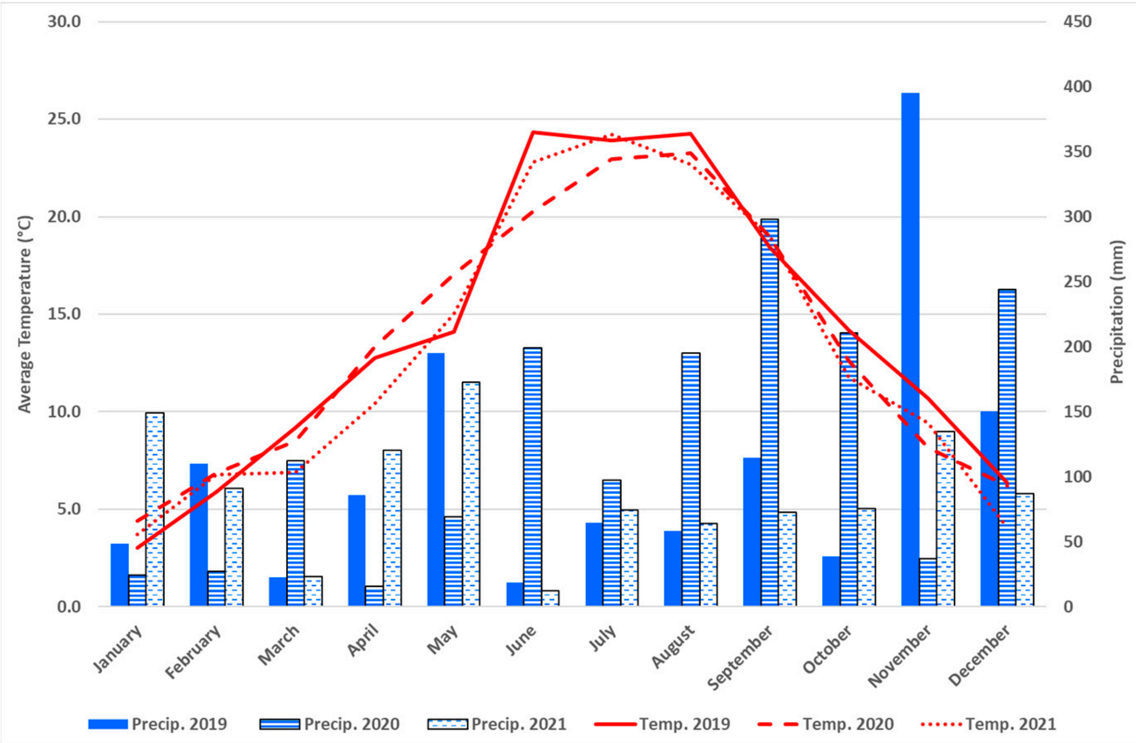

Figure 1. Average monthly temperature (°C) and precipitation (mm) at location Bilje during the study period (2019–2021).

2.3. *Halyomorpha Halys Population Dynamics Monitoring and Trapping Protocol*

Pherocon® Dual Panel Adhesive Trap (15.2 × 30.5 cm) by Trece Inc. (Adair, OK, USA) (Figure 2) and the pyramidal Rescue® Stink Bug Trap (Sterling International Inc., Spokane, WA, USA) (Figure 3) were tested and compared in the study. In all locations, four pyramidal and four sticky traps were alternately deployed along the perimeter of the trees, at a height of ~1.5 m from the ground and 50 m apart, in the border rows of the orchard. Both types of trap were baited with 5 mg of aggregation pheromone composed of the stereoisomers (3S,6S,7R,10S)-10,11-epoxy-1-bisabolen-3-ol and (3R,6S,7R,10S)-10,11-epoxy-1 bisabolen-3-ol and 50 mg of the MDT synergist methyl (E,E,Z)- 2,4,6-decatrienoate (Trécé, Inc., Adair, OK, USA). Traps were checked weekly from the end of March to the end of November (36 consecutive weeks). During each sampling date, the number of *H. halys* adults and nymphs captured in the traps was counted and recorded. Trécé lures were replaced every 12 weeks and clear sticky panels were replaced every 4 weeks.

Figure 2. Pyramidal Rescue® Stink Bug Trap.

Figure 3. Pherocon® Dual Panel Adhesive Trap.

2.4. Landscape Diversity Analysis

In this study, a spatial analysis was performed to evaluate the landscape diversity of each trapping location. The spatial analysis was conducted using Esri's geographic information system (GIS) mapping software ArcGis 10.2.1., and the Agricultural and Forestry Land Use Database, which is the official national database of agricultural and forestry land use in Slovenia [57], was used in analyses. The basic element in the database is a land use polygon which represents the unique part of the land with the same land use [58].

A 300 m radius buffer around trapping locations was calculated and covered with a land-use layer (Figure 4). As part of the buffer area around the trapping location in Miren intersects the territory of Italy, we performed a simple manual classification of land-use units based on DOF050—orthophoto [59] for this area. All data were then analysed using MS Access and MS Excel for further interpretation. Land use was classified into the following thirteen categories: arable land, orchard plantations, vineyard, greenhouse, extensive orchards, olive groves, permanent grassland, fallow land, overgrown farmland, trees and bushes, forests, urban land and water. We also calculated the Shannon diversity (H′) index to measure land cover heterogeneity based on the proportion of land cover types (in %) within the 300 m buffer zone [60].

$$H' = \sum_{i=1}^{n} (P_i * \ln P_i)$$

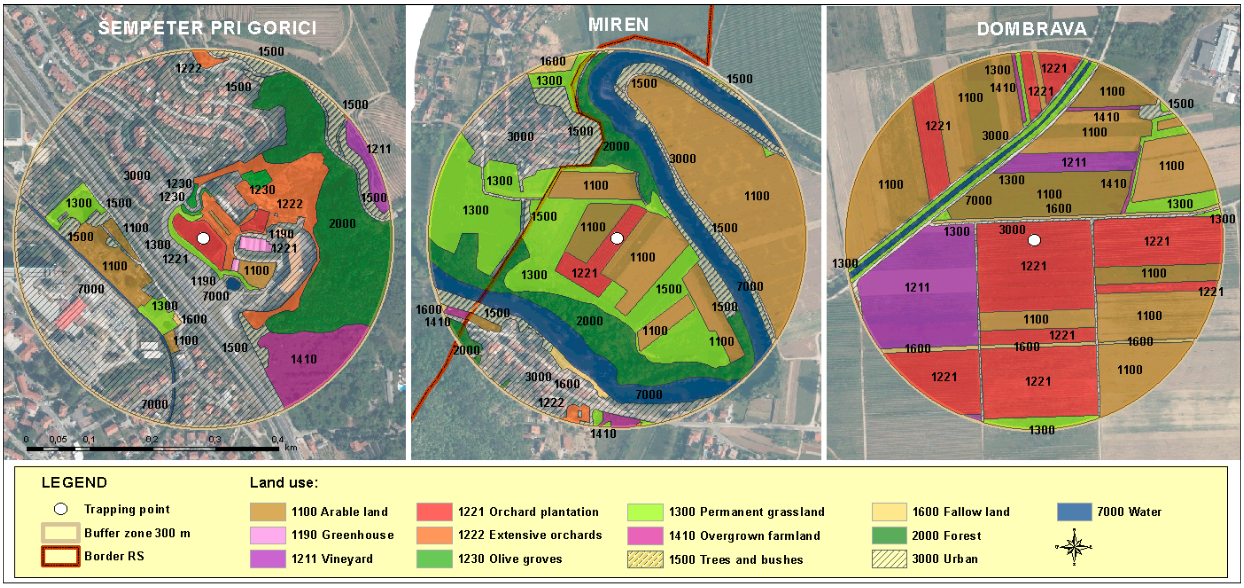

Figure 4. Map of *Halyomorpha halys* trap locations (Šempeter, Miren and Dombrava) and land use within a 300 m radius buffer around trapping locations.

2.5. Data Analysis

The seasonality of *H. halys* adults and nymphs was determined by calculating the daily averages of captures in each trap, location and year, and data are presented as sampling dates. Each sampling season was divided into three sampling periods with equal trapping intervals (12 weeks) to improve statistical analysis and presentation of the temporal distribution of *H. halys*. The early season refers to the period from the end of March to early June, the mid-season from mid-June to early September, and the late season from early September to the end of November.

Analysis of variance (ANOVA) was conducted to determine the impact of the main variables (sampling period, location, year and trap type) and the interaction between them and the *H. halys* trap catch. Because trap catch data did not conform to a normal distribution, they were log-transformed prior to analysis.

Statistical analyses were performed using Statgraphics Centurion Version 16 (Statgraphics Centurion, 2009), and the results are presented as the untransformed mean ± the standard error (SE). Significant differences ($p \leq 0.05$) between the mean values were identified using the Student–Newman–Keuls honestly significant difference multiple range test.

Multiple linear regression was implemented to analyse and describe the impact of weather parameters on *H. halys* trap catch, with temperature, precipitation, number of rainy days and relative humidity as the explanatory variables. To meet the model assumptions of homoscedasticity and normality, the dependent variables (average number of adults and nymphs) were log-transformed (log (X + 1)).

3. Results

3.1. Seasonal Phenology and Trap Captures Comparison

There were significant differences in the capture of adults ($F = 27.11$; df = 2; $p = 0.01$) and nymphs ($F = 23.11$, df = 2, $p = 0.01$) during the different sampling periods. Early-season captures of adults in traps were significantly lower compared to mid-season and late-season captures in both pyramid and clear sticky traps, while the mid-season and late-season captures were statistically equal for both trap types (Figure 5). The nymphs occurred in the mid and late seasons. Pyramid traps captured significantly more nymphs than clear sticky traps, and the mid- and late-season captures of nymphs in pyramid traps were statistically equal, and there were no differences between the season captures observed in clear sticky traps (Figure 6).

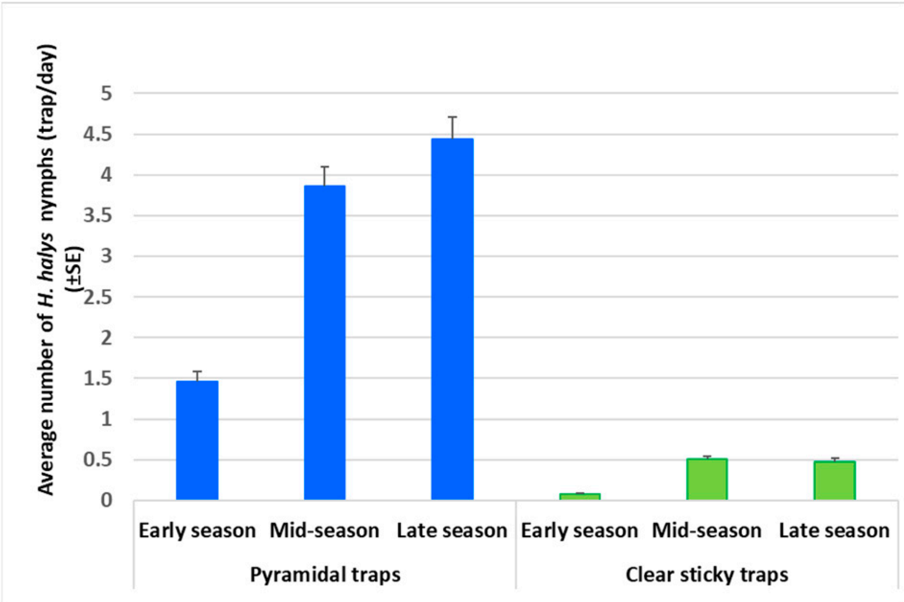

Figure 5. Comparison of the average number of *Halyomorpha halys* adults between seasons in pyramidal and clear sticky traps during the years 2019–2021.

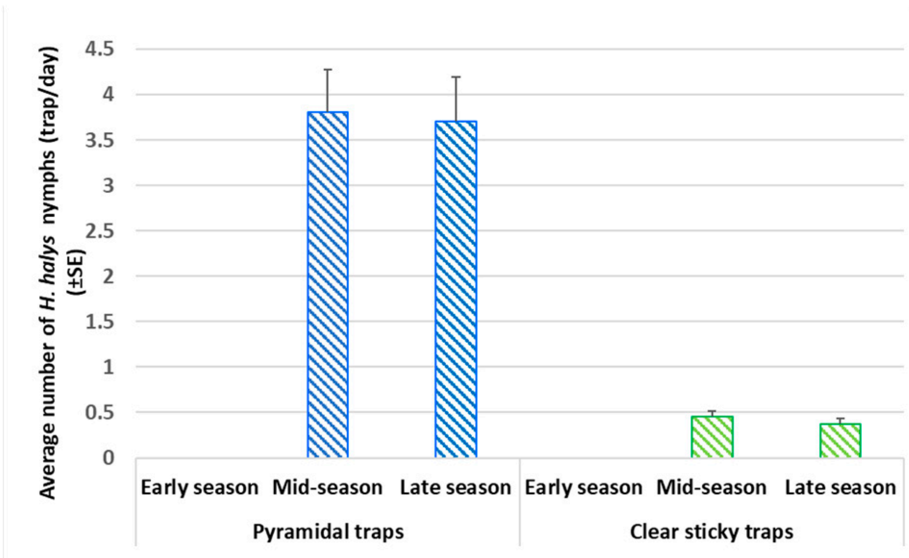

Figure 6. Comparison of the average number of *Halyomorpha halys* nymphs between seasons in pyramidal and clear sticky traps during the years 2019–2021.

Via season-long monitoring and detailed analysis of adult and nymph catches, the existence of two generations per year was confirmed. During the 3-year period (from 2019 to 2021), adult captures increased about six times. Significant differences in the capture of adults ($F = 35.19$, $df = 2$, $p = 0.01$) and nymphs ($F = 37.55$, $df = 2$, $p = 0.01$) were observed between the years.

During 2019–2021, the first adults were found soon after trapping began at the end of March. The capture of overwintering adults began to grow when the average daily temperature exceeded 12 °C. The only distinctive peak capture of overwintering adults was observed in mid-May 2021 (Figure 7). The earliest occurrence of first-generation adults was recorded in 2020 in mid-July, while in the other two years, first-generation adults emerged during the last week of July, with a peak period from the end of July to mid-August. In the 3-year period, the second-generation adults emerged in mid-September and peaked from the end of September to the beginning of October (Figure 8).

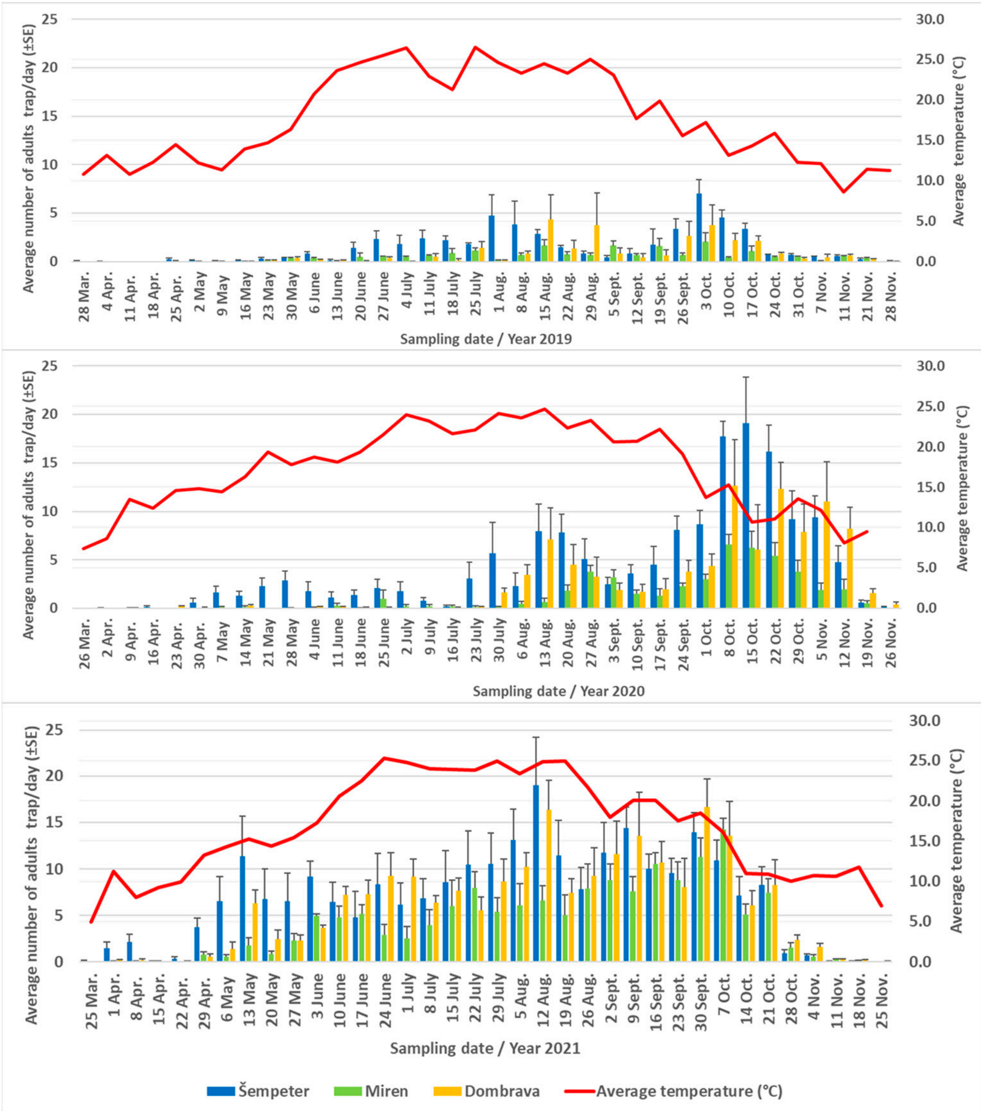

Figure 7. Seasonal occurrence of *Halyomorpha halys* adults in pyramidal Rescue® Stink Bug Traps in apple orchards (Šempeter, Miren, and Dombrava) in Goriška region during 2019–2021 in relation to average temperature.

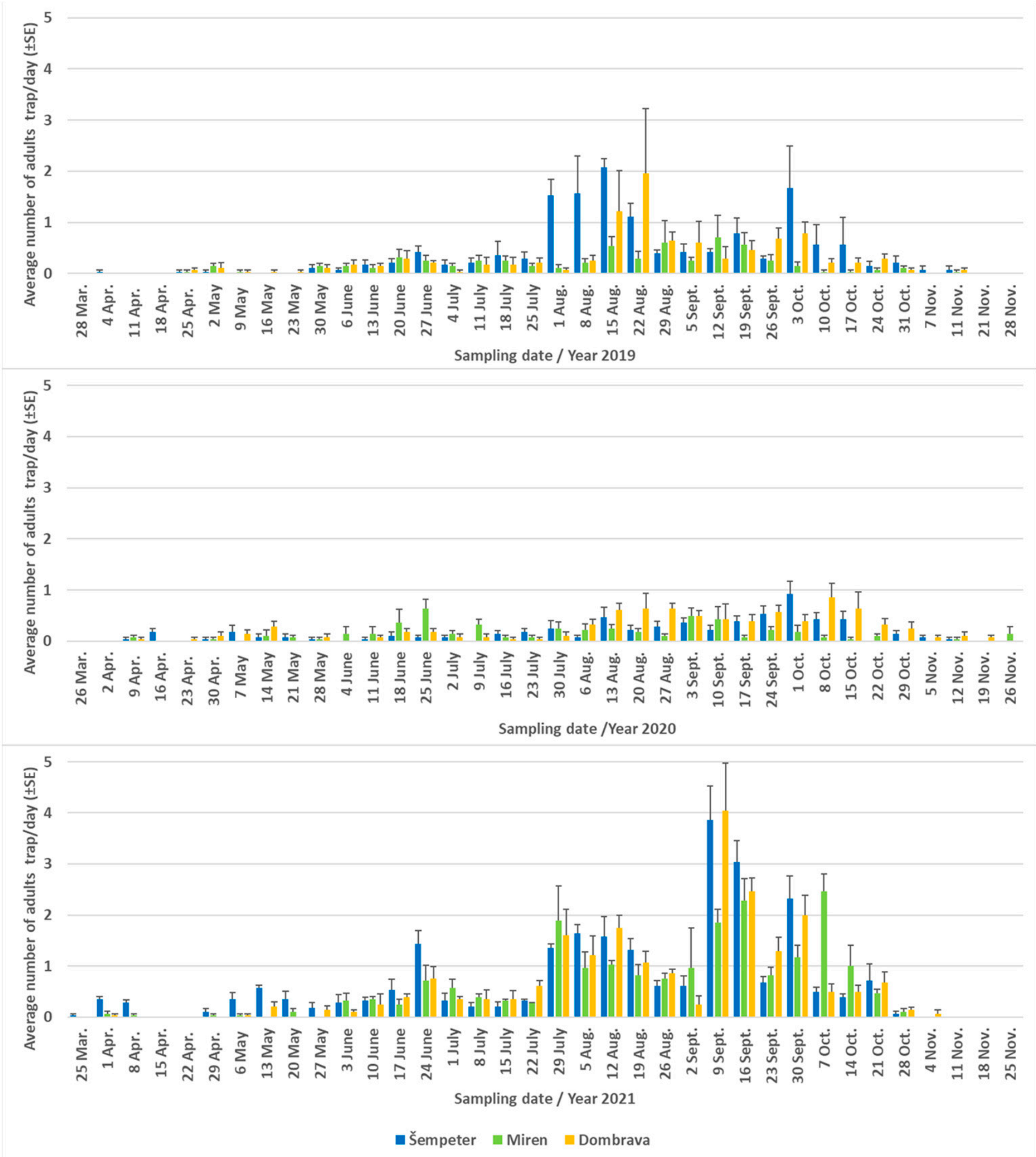

Figure 8. Seasonal occurrence of *Halyomorpha halys* adults in clear sticky traps in apple orchards (Šempeter, Miren, and Dombrava) in Goriška region during 2019–2021.

The earliest date of first-generation nymphs occurrence was recorded in 2019 when the early instar nymphs (N2) were caught on sticky traps between 7 June and 14 June (Figure 9). In general, in all locations, the first-generation nymphs began to emerge from mid-June onwards. In all three years, the trap captures of first-generation nymphs were very low compared to the second generation, almost constant from mid-June to the end of July, without distinct peaks (except in 2021, when the observed nymph counts slightly increased at the end of June). The trap captures of second-generation nymphs were the most numerous in 2020 when nymph densities peaked from early August to early September (Figure 10).

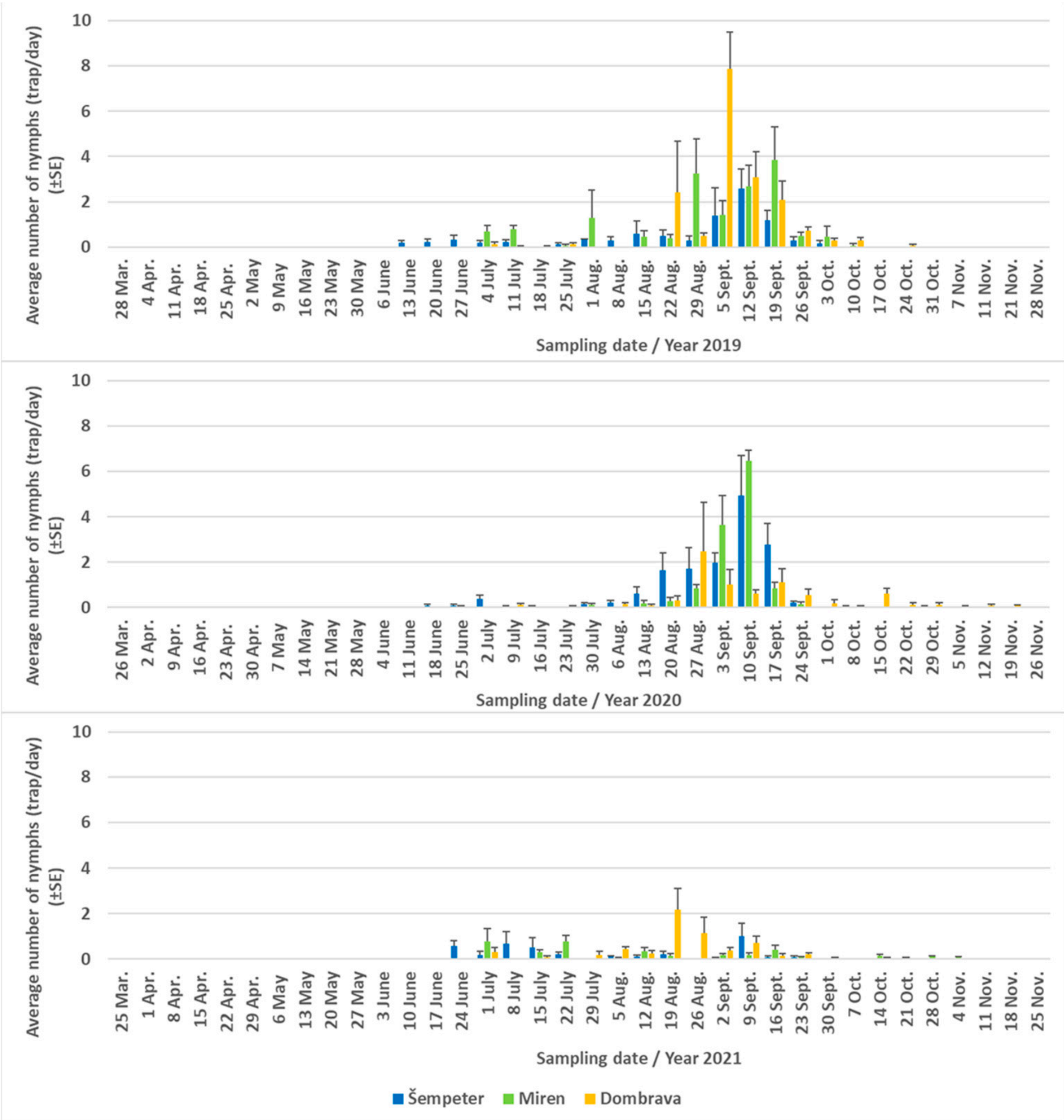

Figure 9. Seasonal occurrence of *Halyomorpha halys* nymphs in clear sticky traps in apple orchards (Šempeter, Miren, and Dombrava) in Goriška region during 2019–2021.

3.2. Trap Type Comparison

Trap type had a significant effect on *H. halys* adult and nymph captures. Pyramidal traps on average caught about nine times more adults per day than clear sticky traps (F = 270.45, df = 1, p = 0.001) and also on average nine times more nymphs per day (F = 45.11, df = 1, p = 0.05). There was significant interaction between sampling period × trap type, (F = 33.33, df =2, p = 0.01) and (F = 22.58, df = 2, p = 0.001); location × trap type, (F = 14.32, df = 2, p = 0.01) and (F = 45.99, df = 2, p = 0.01); year × trap type, (F = 34.05, df = 2, p = 0.001) and (F = 9.15, df = 2, p = 0.01); sampling period × year × trap type, (F = 13,42, df = 4, p = 0.01) and (F = 10,93, df = 4, p = 0.01); location × year × trap type, (F = 10,33, df = 4, p = 0.01) and (F = 3.55, df = 4, p = 0.05); sampling period × location × year × trap type, (F = 20.10, df = 8, p = 0.01) and (F = 17.33, df = 8, p = 0.01), for adults and nymphs, respectively (Table 2).

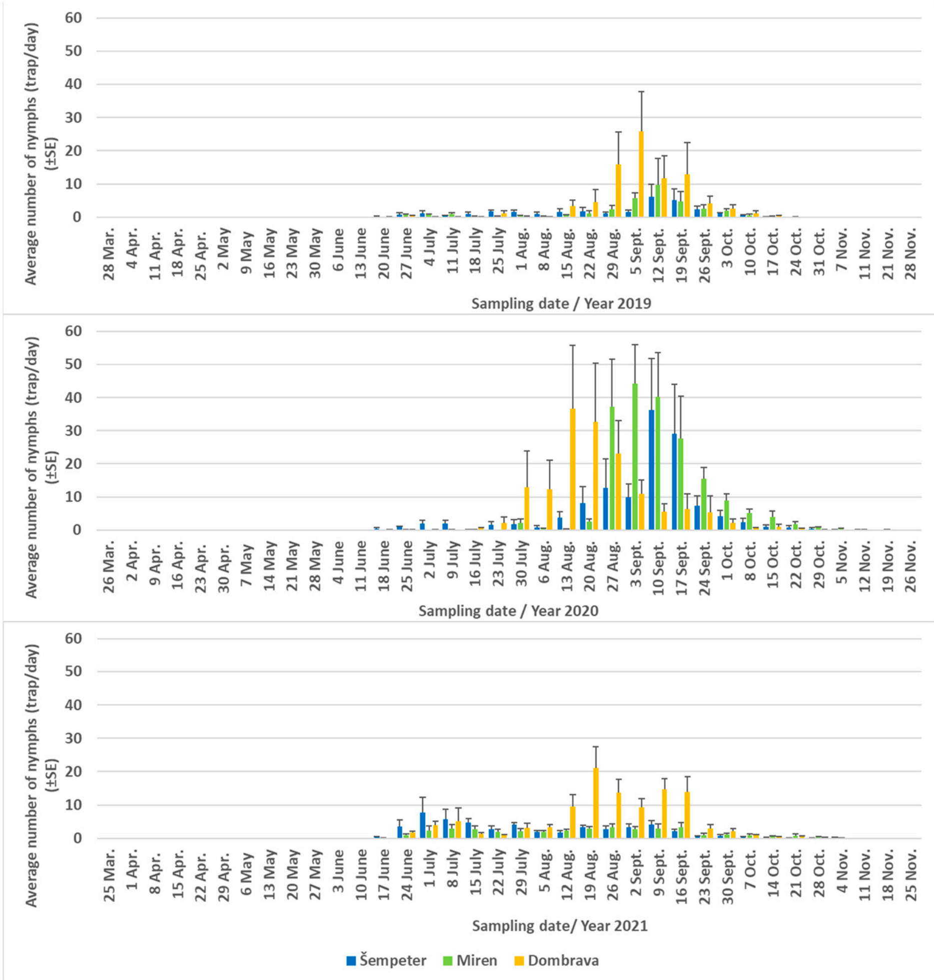

Figure 10. Seasonal occurrence of *Halyomorpha halys* nymphs in pyramidal Rescue® Stink Bug Traps in apple orchards (Šempeter, Miren, and Dombrava) in Goriška region during 2019–2021.

Table 2. Summary statistics of ANOVA (type III sum of squares) for the main effects and associated interactions of *Halyomorpha halys* catches in pheromone traps.

Source of Variation	Adults			Nymphs		
	df	F-Ratio	*p*-Value	df	F-Ratio	*p*-Value
Sampling period (S)	2	27.11	**	2	23.11	**
Location (L)	2	15.91	**	2	43.29	**
Year (Y)	2	35.19	**	2	37.55	**
Trap type (T)	1	270.45	***	1	45.11	**
S × L	2	55.77	**	2	13.45	**
S × Y	2	9.11	***	2	24.73	**
S × T	2	33.33	**	2	22.58	***
L × Y	4	21.33	**	4	23.99	**
L × T	2	14.32	**	2	45.99	**
Y × T	2	34.05	***	2	9.15	**
S × Y × T	4	13.42	**	4	10.93	**
L × Y × T	4	10.33	**	4	3.55	*
S × L × Y × T	8	20.10	**	8	17.33	**

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

When comparing capture efficiency, the difference between the two traps was the smallest at a low density of *H. halys* in 2019, when on average three times more adults and nymphs were captured in pyramid traps than on clear sticky traps (Figure 11). The largest difference in captures was recorded in 2020 when pyramid traps caught fifteen times more adults and seventeen times more nymphs than clear sticky traps (Figure 12).

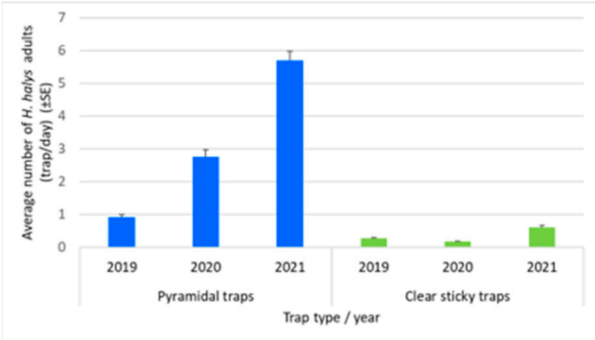

Figure 11. Comparison of the average number of *Halyomorpha halys* adults per day in pyramidal traps during the years 2019–2021.

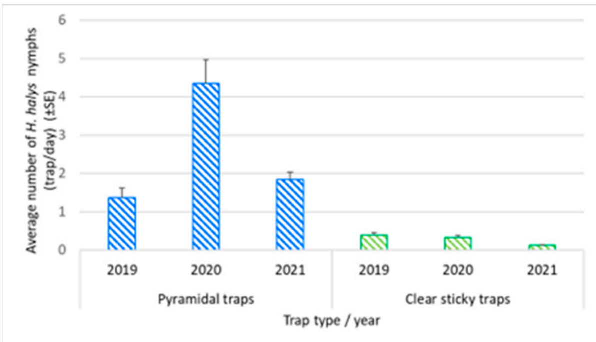

Figure 12. Comparison of the average number of *Halyomorpha halys* nymphs per day in clear sticky traps during the years 2019–2021.

In addition to an increased *H. halys* captures in 2020, the difference in captures between traps was likely driven by a high amount of precipitation that could weaken the performance of the sticky traps. In the period from March to October 2020, two times more precipitation fell than in the same period in 2019 and 2021. The captures of *H. halys* adults in pyramid traps considerably increased in *H. halys* over a three-year period. In general, an increasing trend in captures was observed in clear sticky traps, but with a noticeable drop in 2020 (−36%), the reasons of which are already mentioned above.

3.3. Location and Surrounding Landscape Diversity Comparison

The trapping location affected the adult captures ($F = 15.91$, $df = 2$, $p = 0.01$) and nymphs ($F = 43.29$, $df = 2$, $p = 0.01$). Over all the study years, the highest average number of adults was recorded at location 1 (Šempeter).

High captures of adults were also recorded at the other two locations, particularly in 2021, when a high increase in *H. halys* tarp captures was observed in the study area (Figure 13). During the 3-year study period, on average, the highest number of nymphs was caught in the apple orchard at location 3 (Dombrava). Otherwise, a high increase in nymph catch was observed in 2020 at all locations within the study area, with no significant difference in captures between locations. The peak occurrence of nymphs reached in 2020 was followed by a huge decline at all locations during the last monitoring season in 2021(Figure 14).

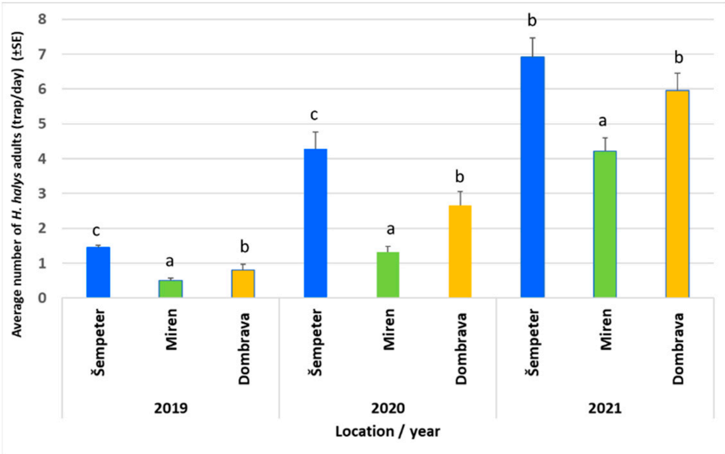

Figure 13. Comparison of average (±SE) number of *Halyomorpha halys* adults in apple orchards from different locations (Šempeter, Miren, and Dombrava) in Goriška region during 2019–2021. Means with the same letters within each year are not significantly different ($p > 0.05$ ANOVA followed by the Student–Newman–Keuls test).

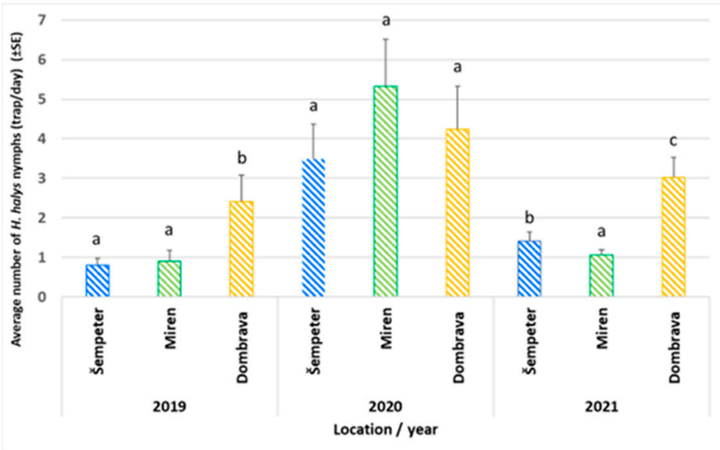

Figure 14. Comparison of average (±SE) number of *Halyomorpha halys* nymphs in apple orchards from different locations (Šempeter, Miren, and Dombrava) in Goriška region during 2019–2021. Means with the same letters within each year are not significantly different ($p > 0.05$ ANOVA followed by the Student–Newman–Keuls test).

Landscape diversity within the study area was analysed using spatial analysis of a buffer zone with a radius of 300 m around each trapping location (apple orchard). Based on the results of the spatial analysis, 13 land-use categories were identified. We found the most diversified surrounding landscape at location 1 (Šempeter pri Gorici), with all 13 categories of land use. The most encountered was urban land, occupying 60.1% of the buffer zone (Figure 15), followed by agricultural land (16.9%) and forest (13.7%). Location 2 (Miren) was characterized by extensive agricultural land cover, occupying one-half of the area (50.2%), with arable land and permanent grassland as the predominant types of land use. Urban areas represented 15.6% of surrounding land use, and water and forest covered 14.6 and 11.5% of the land, respectively. The apple orchard at location 3 (Dombrava) was situated within an area of intensive agricultural land use. Almost 95% of the land was cultivated. Arable land (42.2%), orchard plantations (32.1%) and vineyards (13.1%) represented the great majority of the total agricultural land cover. This location was also characterized by a low share of overgrown land (0.6%) and a low share of land covered with trees and bushes (0.3%), and there was no forest in the surrounding landscape.

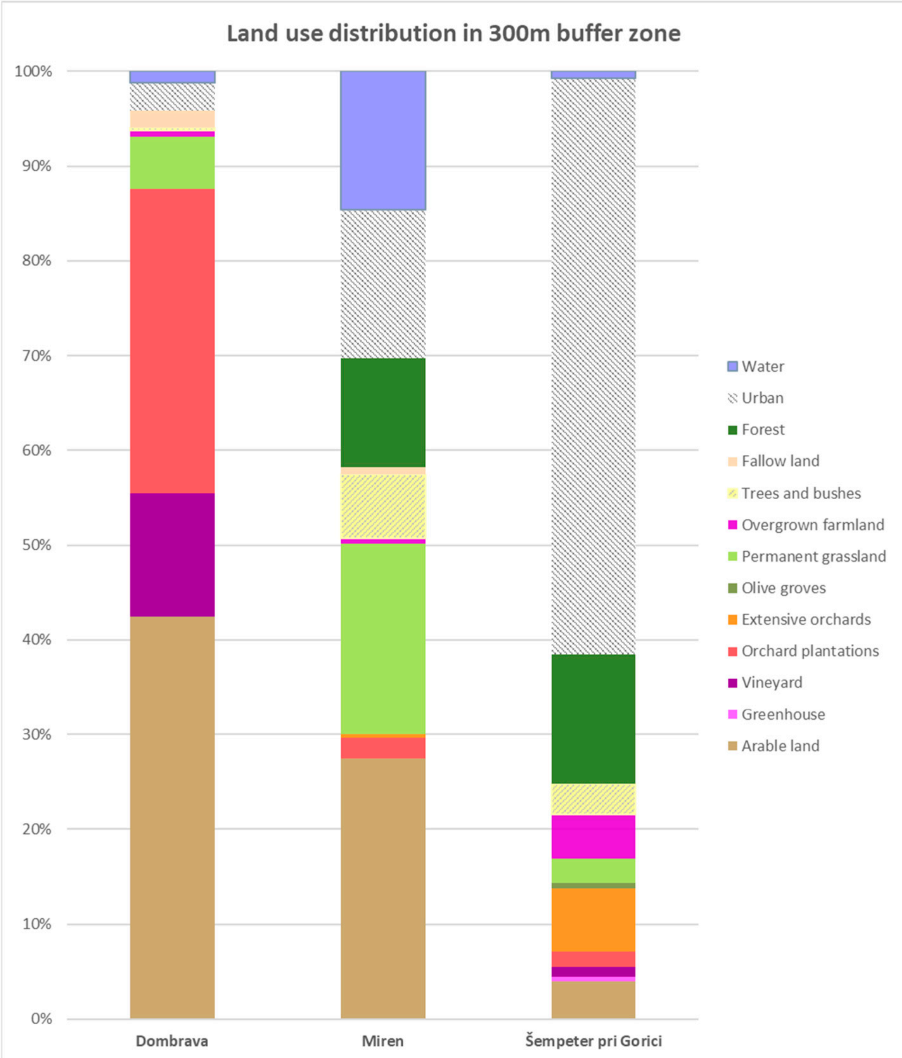

Figure 15. Percentage of different land-use types per landscape radius 300 m surrounding each studied location (apple orchard) in the Goriška region.

The Shannon diversity indices of location 1 (Šempeter), location 2 (Miren) and location 3 (Dombrava) were 2.4229, 2.1301 and 1.9738, respectively. The index values support the results of the spatial analysis of land-use diversity at each location.

Comparing *H. halys* captures in apple orchards and land land-use diversity in the buffer zones, we found some positive relationships. *Halyomorpha halys* captures were most abundant in location 1 (Šempeter), with the highest landscape diversity identified and with the highest share of urban land (buildings, roads, parking spaces, etc.) and overgrown farmlands, which can serve as a reservoir to boost the *H. halys* population.

3.4. The Effect of Weather Variables on Seasonal Abundance of Halyomorpha halys Population in Goriška Region

Multiple linear regression was used to describe the impact of weather (independent) variables (temperature, precipitation, number of rain days and humidity) on *H. halys* population (the dependent variable). Weather data for the period from the end of March to the end of November (36 weeks) between 2019 and 2021 were included in multiple linear regression models, together with log-transformed data for *H. halys* adults and nymphs captured for the same period.

The established model for *H. halys* adults was statistically significant (R^2 = 0.734, F = 21.417, p < 0.0001). In total, 73% of the variance in the *H. halys* adult population could be accounted for by the four weather parameters, among which average temperature and relative humidity had the highest impact (Table 3). Although the amount of rainfall was less important, the number of rainy days significantly reduced the *H. halys* adult population during the season. Similar results were obtained when analysing the impact of the weather parameters on the seasonal abundance of *H. halys* nymph. Within the statistically significant model (R^2 = 0.700, F = 18.114, p < 0.0001), the average temperature had a major impact on the nymph population. The growth of the nymph population was also accelerated by precipitation, whereas the number of rainy days had a significant negative effect (Table 4).

Table 3. Multiple regression associations of *Halyomorpha halys* adults captured, with weather variables (temperature, precipitation, number of rain days and humidity).

Independent Variables	Coefficient Value	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)
Average temperature weekly (°C) (TW)	**0.722**	0.095	7.575	***	0.528	0.917
Average precipitation per week (mm) (PW)	0.192	0.128	1.496	0.145	−0.070	0.454
Number of rain days per week (NRD)	**−0.429**	0.115	−3.736	**	−0.664	−0.195
Relative humidity (%) (RH)	**0.625**	0.116	5.401	***	0.389	0.861

Signification codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05.

Table 4. Multiple regression associations of *Halyomorpha halys* nymphs captured, with weather variables (temperature, precipitation, number of rain days and humidity).

Independent Variables	Coefficient Value	Standard Error	t	Pr > |t|	Lower Bound (95%)	Upper Bound (95%)
Average temperature weekly (°C)	**0.726**	0.101	7.165	***	0.519	0.932
Average precipitation per week (mm)	**0.306**	0.136	2.242	*	0.028	0.584
Number of rain days per week (NRD)	**−0.660**	0.122	−5.412	***	−0.909	−0.412
Relative humidity (%) (RH)	0.145	0.123	1.179	0.247	−0.106	0.396

Signification codes: 0 < *** < 0.001 < ** < 0.01 < * < 0.05.

4. Discussion

4.1. Population Dynamics

The results of this season-long monitoring of the *H. halys* population over a 3-year period in apple orchards provide important new knowledge of the phenology of the species in Western Slovenia, which could also be applied more widely to other European regions with sub-Mediterranean and Mediterranean climates. The migration of *H. halys* adults from overwintering shelters started at the end of March, and their movement towards the available hosts intensified during April and May. The first mass occurrence of adults in apple orchards coincided with the phenological phase of early fruit development. The second peak of adults was observed from late July to early August, about two weeks after the emergence of first-generation adults. The third and highest peak that followed the emergence of second-generation adults occurred from the end of September to the beginning of October and was reinforced by the aggregation behaviour of the adults prior to hibernation. Similarly, two peaks of nymphs were observed; first, a lower peak in July corresponded to the first generation, and the second at the end of August, related to the second generation of *H. halys.* Our field research confirmed the previously known data on *H. halys* phenology in Slovenia [45] and provided detailed information on its seasonality and trap catch. Data on phenology were comparable to those obtained in Italy [61,62], although we found notably higher trap catches. A similar study performed in apple orchards in South Tyrol [52] in 2019 demonstrated a population peak at the end of September, with a weekly average of 18.05 adults per trap, while our data for the same period showed considerably higher values, with a weekly average of 30.33 to 49.25 adults per trap. Regarding the total trap catch, in South Tyrol, an average of 119 adults per site was found; in the same season, we observed an average of 230 adults per site. While there was a trap catch decline observed in the orchards of South Tyrol in 2020, the Goriška region faced a high increase; in 2020, trap catches tripled, while in 2021, *H. halys* trap catches increased six-fold (n average 1520 adults per site). A high increase in *H. halys* captures during the growing seasons was also reported in the early stages of the *H. halys* invasion in the United States, Northern Italy and Romania [31,61,63].

4.2. Trap Efficiency

Pyramid traps baited with Trécé lures captured a significantly higher number of adults and nymphs than clear sticky traps. The difference between the two trap types increased from season to season as the *H. halys* trap catches grew. Recently, pyramid traps using rescue baited with different lures have been evaluated in different comparative trap efficiency studies. According to Morrison et al. [32], in apple orchards, rescue pyramid traps were significantly less effective in trapping adults and nymphs than ground-deployed standard black pyramid traps and less effective than other small limb-attached pyramid traps. Vaccari's study [64] found them to be equally effective as large coroplast pyramid traps, while both types were baited with Trécé lures. A good performance of rescue pyramid traps was also found by Zapponi et al. [35] in a vibrotrap evaluation study when they were used as a standard trap for comparison. Due to their commercial availability, they were implemented in an *H. halys* long-term monitoring program in South Tyrol, exhibiting the highest trapping efficacy when baited with Trécé lures [62]. Although we found that clear sticky traps captured significantly lower numbers of *H. halys* adults and nymphs than pyramid traps, they accurately described the seasonal dynamics of *H. halys*, including the first occurrence of adults, as well as all subsequent important stages in pest development. No significant differences were observed between the two types of traps at the very beginning of the season in low-density populations of *H. halys*. Since a serious threat of *H. halys* spread in Europe has emerged, this kind of trap was widely used as an effective tool in surveillance programmes for the early detection of new pests. By using the same traps, the first appearance of *H. halys* in Slovenia was confirmed in 2017 [55], and they were also used to track the spread of the pest throughout the country in the following years [56]. Clear sticky traps have already demonstrated adequate performance at catching *H. halys* in previous studies. In addition to efficiency, the authors emphasised their simplicity of use and cost benefits [34,65,66]. Therefore, we agree with the recommendation of Rice et al. [34] that further improvement in *H. halys* monitoring traps should be orientated to reduce the costs and labour associated with deployment and maintenance.

Prolonged *H. halys* retention in the vicinity of a trap due to a phenomenon known as "trap spillover" and increased fruit injury on baited trees as adverse side effects of using *H. halys* aggregation pheromone were reported in most of the studies concerning this field, especially when Trécé lures were used [19,24,35,67]. Although our study did not aim to assess fruit injuries, parallel evaluations made by a separate study in the same orchards showed that fruit injuries from trees adjacent to traps can be up to 20% higher compared to those away from traps [68]. So, the best place for trap positioning to avoid such side effects remains to be determined. In order to avoid crop damage, fruit growers prefer to deploy them outside the orchards [19], raising the question of whether captures outside the orchard reflect the actual insect pressure in the orchard and risk crop damage. According to Zapponi et al. [35], these problems can be resolved by increasing trap effectiveness. They suggested upgrading pheromone traps with vibration signals to increase the number of captures in the trap.

In general, exceptionally high captures found in the traps placed in apple orchards during our study can be partly explained by previous research that found apples as a less suitable host for *H. halys* and also less competitive with pheromone-baited traps in *H. halys* attraction, particularly when compared to peach [69,70]. Otherwise, apple is reported as a common host for *H. halys* in its native range [71], as an early season host fruit [51], and among the most acceptable hosts in invaded areas [24], as confirmed by our long-term monitoring of *H. halys* in apple orchards. Recently, we found apple to be a good *H. halys* oviposition host compared to other agricultural crops [72], and in this study, we found it to be a suitable host and an entire-season available food source for *H. halys* adults and nymphs. *Halyomorpha halys* is considered a season-long pest in apple orchards, its growing season aligns well with that of apples [72]. The large population found in apple orchards is the result of population buildup during the growing season, as well as the consequence of adult migration from surrounding landscape vegetation that occurred after the harvest of peaches and pears in mid-August and at the end of August, respectively. Both fruit species are widely distributed in the Goriška region and are also known as highly suitable hosts for *H. halys*. In our opinion, the apple could arguably be considered the most threatened fruit species in the region, due to the long growing season and its cultivation within the area of intensive land use and agricultural production that support high-density populations of *H. halys*.

In our study, temperature and relative humidity were found to be the most important abiotic factors affecting the *H. halys* population dynamic and abundance during the season. Although average precipitation did not have a significant impact on adult captures in the traps, the number of rainy days significantly decreased the number of nymphs and adults. These findings are consistent with previous studies that found hot and dry climates unfavourable for *H. halys* and may limit its geographical range [53,73,74]. Temperature is the most important abiotic factor that affects herbivorous insects by directly influencing their survival, development, distributional range and abundance [75,76]. During the 3-year research period, we did not detect weather extremes that would have a notable impact on *H. halys* trap catch growth or decline. The average monthly temperature during summer months ranged from 22 to 24 °C, which is optimal for population development and for *H. halys* trap capture increases [77]. High temperatures above 36 °C, which have been experimentally proven to increase the mortality rate of nymphs and adults [42,43,54,78,79] appeared only once in the 3-year period. A multi-day high-temperature event that occurred in August 2021 resulted in a short-period decline in adult and nymph captures, but did not affect the total trap catch. However, *H. halys* adults are able to withstand higher temperatures if the exposure time is shorter [80,81]. Venugopal et al. [54] found a strong negative relationship between *H. halys* abundance and average temperatures in June (above 23.5 °C). Similar temperature conditions appeared in the first year of our research, in June 2019. However, we cannot fully confirm their findings because, despite the warm June, *H. halys* adults and nymphs were constantly present in all trapping locations. Sap-feeding insects, including stink bugs, can be strongly affected by moisture, particularly during nymphal development as well as in the adult stage [75]. Khadka et al. [80], who investigated relative humidity impact on *H. halys* development, found that egg hatch and nymphal survival were the highest at a humidity range between 55 and 90%. The humidity conditions during our research were favourable and comparable to the aforementioned range. Throughout the summer, relative humidity ranged between 72 and 77% and made a significant contribution to the increase in *H. halys* trap capture. By tracking the population dynamics and abundance of *H. halys* together with weather conditions over several years, it is becoming clear that *H. halys* can be established in the Slovenian territory and proliferate within an area with similar climate conditions as in the Goriška region, assuming a wide range of host plants are available.

The type of land use that displayed the most positive relationships with *H. halys* trap captures was urban land. Agriculture–urban interface, common in the Goriška region, is an ideal space for *H. halys* population growth according to Walner et al. [46], offering both cultivated and wild host plants for development and also natural and human-made overwintering shelters. In the first period after the initial establishment, urban landscapes with commercial and residential facilities provide protection and enable the overwintering survival of *H. halys* [82]. Urban trees, ornamental hosts and unmanaged wooded areas near suburban regions are critical for the initial *H. halys* population establishment [83,84]. On the other hand, established urban populations pose a risk to fruit trees and field crops grown in close proximity [85]. In our study, the apple orchard adjacent to the urban area contained the highest density of *H. halys* in the three-year period. According to spatial analysis data and the Shannon diversity index, the landscape diversity found in the border zone surrounding this orchard was also the highest among the studied locations, with a high proportion of forest and the presence of overgrown farmland. As they are non-managed, these two types of land use tend to be important for the building-up of early-season populations, as well as season-long reservoirs for the dispersal of adults to agricultural crops and an important factor for crop infestations [84]. Wallner et al. [46] found landscapes rich in urban land supporting higher *H. halys* density during the initial invasion and establishment; later in the phase of population growth and dispersion, the pest abundance was closely linked to urban areas, semi-natural habitats and agricultural land. Our study provides additional support for understanding population dynamics during phases of intensive population growth and range expansion. In addition, in the agriculture–urban interface, we found intensive agricultural land use to promote *H. halys* population growth, principally when *H. halys* preferred hosts are cultivated. The continuous presence of all *H. halys* developmental stages in the apple orchard located within the intensive agricultural landscape supports our assumptions that *H. halys* populations can be built up in apple orchards during the season. In the last year of monitoring, *H. halys* trap catches increased in both locations, in the orchard adjacent to the urban area and within the agricultural intensive area and reached the same level at the end of the season.

Data on the surrounding landscape vegetation indicate that the total trap catches were most likely enhanced by the migration of the pest from the border area. Berg et al. [67] who investigated the border habitat effect on *H. halys* population density in apple and peach orchards, found that non-managed woodland borders contributed the most to population abundance in orchards, while adjacent orchards also contributed substantially to captures and fruit injury at harvest. In general, our findings are also consistent with the results of Tamburini et al. [48], who established landscape composition as a key factor driving the dynamics of *H. halys* in agroecosystems. Their study found that landscape composition influenced the abundance of trapped *H. halys* in fruit orchards. As noted by Emery et al. [86], in general, the high intensity of agriculture at the landscape level benefits pests, whereas low-intensity practices at the local level mitigate these effects. In our study, higher trap catches were recorded in urban and intensive agricultural areas, and populations were notably smaller in the apple orchard within an area of extensive agricultural land use, with a high proportion of unmanaged permanent grassland, forest and riparian vegetation consisting of trees and bushes.

5. Conclusions

This study contributes to the increasing knowledge on the seasonality of *H. halys* population dynamics and interactions with climate, affecting its abundance and potential for causing crop losses. Understanding these complex relationships is essential for implementing integrated pest management (IPM) strategies to prevent crop damage. The results obtained in this study can also be applied in building forecasting models as a decision-making support tool.

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