

Article

Evaluation of Asian Hornet (*Vespa velutina*) Trappability in Alto-Minho, Portugal: Commercial vs. Artisanal Equipment, Human Factors, Geography, Climatology, and Vegetation

Fernando Mata ^{1,*} , Joaquim M. Alonso ^{2,3} and Concha Cano-Díaz ¹ 

¹ CISAS—Center for Research and Development in Agrifood Systems and Sustainability, Instituto Politécnico de Viana do Castelo, 4900-347 Viana do Castelo, Portugal; diazmaria@ipvc.pt

² PROMETHEUS—Research Unit on Materials, Energy and Environment for Sustainability, Instituto Politécnico de Viana do Castelo, 4900-347 Viana do Castelo, Portugal; malonso@esa.ipvc.pt

³ Escola Superior Agrária, Instituto Politécnico de Viana do Castelo, 4990-706 Ponte de Lima, Portugal

* Correspondence: fernandomata@ipvc.pt

Abstract: Trapping the Asian hornet remains a viable alternative to monitor its presence, dispersion, and ecological niche. With the objective of evaluating the effectiveness of baits and traps, an Asian hornet (*Vespa velutina*) capture trial was conducted using combinations of artisanal and commercial baits and traps. The second objective was to explore the relationship between the species' dispersal patterns and the influence of human, geography, climate, and vegetation factors, to identify the preferred conditions for its colonization. We identified beekeepers in the Alto Minho region of Northern Portugal, where the different combinations of baits and traps were placed. The traps were monitored from February to September 2023, and the captures were counted. The temporal variation of the captures showed a first peak at the beginning of April, corresponding to primary workers. In September, when the trial was halted, the second peak, corresponding to secondary workers, had not yet been reached. The peaks of captures were used to fit models to allow the characterisation of their ecological niche. Statistical analysis of the captures revealed no significant differences. It was concluded that there is no advantage in using the commercial devices and baits tested. The ecological niche where the higher number of captures is observed is characterised by an abundance of vegetation, humidity, and higher temperatures. Elevation and slope also favour the presence of the Asian hornet.

Keywords: Asian hornet; attractants; baits; ecology; honeybee; invasive species; traps; *Vespa velutina*



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1. Introduction

The Asian hornet (*Vespa velutina*) is indigenous to Southeast Asia and has invaded several countries where it is becoming increasingly common [1]. It arrived in Europe through France in 2004 [2] and has spread to Navarra, Spain (2010) [3], Minho, Portugal (2011) [4], Belgium (2011) [5], Italy (2012) [6], Germany (2014) [7], Great Britain (2016) [8], The Netherlands (2017) [9], Switzerland (2017) [10], Luxembourg (2020) [11], Czechia (2023) [12], and Austria (2024) [13]. Surveillance has become mandatory in the EU as the Asian hornet (AH) is listed as an invasive alien species of Union concern through the EU Regulation 1141/2016 [14].

The AH predaes on the honeybee (*Apis mellifera*) and has become a major concern for its capacity to destroy apiaries [15]. It has become an invasive species without competitors or natural predators in Europe and has negatively impacted biodiversity [16], the economy [17], and human health [18]. In temperate regions, the AH life cycle is annual, due to food scarcity and the cold in winter, making it difficult to maintain social life throughout the year [19]. The life cycle includes four main phases starting from the founding of the

colony, the growth phase, the reproduction phase, and the intermediate phases, including the queen's diapause time [20].

In Europe, the first queens are generally observed in February when temperatures rise. After winter, they begin the biological cycle by building the primary nest around March. As the colony expands, the number of workers increases reaching its maximum size at the end of the summer season [19,20]. The greatest predation of honeybees is recorded during this stage, and the honeybee is a major contributor to the AH diet. The colony can potentially produce thousands of sterile workers, responsible for feeding the colony [19]. With this population growth, they abandon the primary nest to build a larger secondary nest. These nests, spherical and pear-shaped, can measure up to 100 cm in diameter and are mostly built in natural structures, namely in the tops of trees, and constitute the structures normally observed and reported [21]. At this stage, the wasps' development time of the larvae also decreases, taking just 29 days to become a medium-sized worker compared to the 50 days needed in a primary nest [22]. Hence the greater protein needs and honeybee predation, and one AH nest may be responsible for the capture of up to 25 to 50 honeybees daily [23].

In autumn, the dynamics of the colony begin to change, resulting in a gradual reduction in the number of workers. During this period of decline, new queens and males emerge, leaving the nest to mate. The founding queens, after mating, disperse, usually alone or accompanied by two or three individuals, to find a suitable place to survive the winter, while the rest of the colony dies. At the beginning of the following spring, these new queens, who previously mated, are the only survivors, ready to start new colonies and restart the cycle [19,20].

To control the AH, a variety of techniques have been tested, and the most commonly used include nest destruction and trapping using traps with an attractant [2]. The use of traps is the first method used against invasive wasps and intense capture campaigns have been created, often supported by beekeepers and local governments, to reduce the population and minimise their effects [2]. Traps can be commercial or homemade, with specific attractants for each stage of the wasp cycle [20]. During the primary nesting phase, food baits with sugar solutions are most effective [24,25], while during the secondary nesting phase, wasps seek out protein-rich foods [26,27]. In the spring, the objective is to capture the founding queens, responsible for the primary nest, while in the summer, the objective is to capture the workers originating from the secondary nest [26,28].

Capturing workers does not solve the problem; however, it helps to reduce predation pressure on apiaries and is also helpful for the mandatory monitoring within the EU. If used in autumn, when mating occurs, it is possible to capture fertilised wasps and thus help control the species. Despite this, the use of traps has been criticised for not being selective enough to avoid capturing other insects, which could affect local fauna and, consequently, the population dynamics of other species [29]. Developing efficient early detection and control strategies for *Vespa velutina* is critical to mitigating its spread and harmful effects. Implementing systematic monitoring protocols is also essential to curb the expansion of this invasive species. In this context, identifying AH dispersal pathways and understanding the environmental, human, geographic, climatic, and vegetation factors that facilitate its invasion is paramount.

Beekeepers have been using self-fabricated traps and self-produced baits, and the market has also evolved to offer these products at a significant cost. Intending to compare the effectiveness of both artisanal and commercial baits and traps, we have designed and implemented a trial in the Alto Minho region of Portugal and herein reported. It is also intended to observe the temporal variation of captures as well as the differentiation between captures of primary and secondary workers according to different ecological niches.

Artisanal, homemade traps for capturing AHs are devices made at home with simple, low-cost materials, such as PET bottles, wire, cardboard, and adhesive tape. One of the advantages of homemade traps is that they are affordable and easy to make, and anyone can produce them. Furthermore, they are highly customisable and can be adapted to different locations and conditions. In addition, homemade traps can be made with

recycled or reused materials, which makes them a more sustainable option than commercial traps. Furthermore, they allow people to actively involve themselves in controlling the proliferation of the AH in the communities.

In this study, the AH was observed using bait traps placed in regions characterized by diverse landscapes and weather conditions. The first objective of the study is to test and compare the effectiveness of the trapping methods using both artisanal and commercial bait and traps. The second objective of this study is to explore the relationship between the species' dispersal patterns, altitude, and meteorological conditions to identify the preferred conditions for its colonization.

2. Materials and Methods

2.1. Sampling

In collaboration with the APIMIL—Associação dos Apicultores de Entre-Minho e Lima, a local Alto Minho, Portugal, beekeepers' Association—we used a selected number of beekeepers to proceed. Initially, we asked the Association to identify beekeepers with the potential to assume a compromise of monitoring and reporting of readings. From the list given, we randomly selected 30 beekeepers from a total of 584, that could be representative of the region. As such the concentration of sampling points is also coincident with the concentration of beekeepers in the area. While sampling we also ensured that the geographical distribution covered the studied area and the variety of ecological niches in the area. The location of the sampling sites and their distribution can be consulted in Figure 1. The traps, baits, and forms to register the captures in the study were given to the farmers. The farmers were informed about the intent of data collection and have also given explicit consent to use the data in this study. All the beekeepers have also signed a declaration of commitment. The beekeepers used in the sample are regularly trained by APIMIL, and are conversant with AH identification.

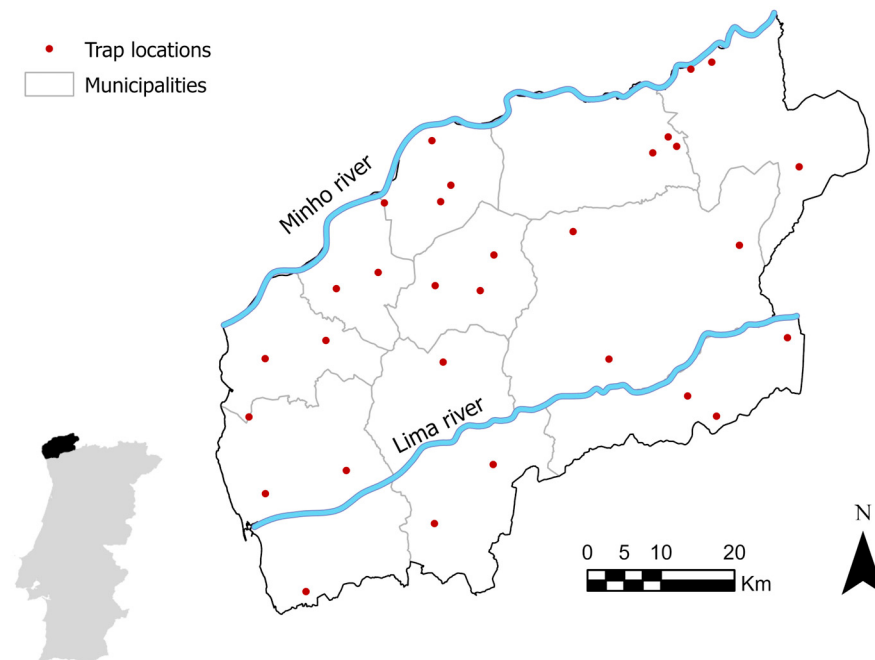


Figure 1. Location and distribution of the sampling points in the Alto Minho region of Portugal.

2.2. Traps and Attractants

Commercial traps for capturing AHs are devices allegedly manufactured by companies specialising in pest control. They are designed specifically to capture this invader and generally use a specific attractant solution, developed based on the species' dietary preferences. Reportedly, another advantage of commercial traps are additional features, such as entry and exit blocking systems, which prevent other species from being accidentally

captured, making them more selective. However, commercial traps are generally more expensive than homemade traps and may be less customisable.

Figure 2 shows the traps used in the study. The commercial traps used in the present study consist of a device to place on the top of a spare bottle, brand JGS, as shown in Figure 2B. The artisanal traps used use the same plastic bottle as the bait container, and instead of the commercial entrance, another plastic bottle positioned perpendicularly is attached to the bottleneck of the container, as shown in Figure 2A.



Figure 2. Examples of artisanal (A) and commercial (B) traps.

The different combinations of trap/attractant were placed near the entrance of the beehives as evidenced by Figure 3.



Figure 3. Placement of the baited traps close to the entrance of the beehives.

The commercial attractant used in this study was the VespaCatch produced by Vétô-Pharma and sold in 10 mL sachets. The artisanal attractant is produced using a mix of water, sugar (100 g per litre of water), and bakery yeast (a coffee spoon per litre of water).

2.3. Human, Geographical, Climatological, and Vegetation Factors

The counts of capture peaks for primary workers and for secondary workers were used as the dependent variables (DVs) in Poisson models fitted using the following independent variables (IVs):

Human-dependent: number of beehives in the apiary, and population density; Climatological: directional albedo, aridity index, mean annual precipitation, mean annual precipitation seasonality, mean annual temperatures, mean annual temperatures seasonal-

ity, and average wind speed; Geographical: distance to the sea, distance to a main river, elevation, slope; Natural: normalised difference vegetation index (NDVI).

The information about the number of beehives in the apiary was obtained directly from the beekeeper. The human population density expressed as residents/km² (year 2020) was obtained from the Gridded Population of the World, Version 4 [30]. The directional albedo quantifies the fraction of irradiance reflected by the surface of the Earth. The dataset used was obtained from Copernicus, is dimensionless and is defined as the “integration of the bi-directional reflectance over the viewing hemisphere” [31]. The Aridity Index indicates the relationship between precipitation and evapotranspiration, representing the water demand of vegetation, calculated on an annual basis. In this context, higher Aridity Index values correspond to more humid environments, while lower values indicate more arid conditions. In the dataset used [32], the values have been multiplied by 10,000 to enhance the precision without resorting to the use of decimal points.

The mean annual precipitation (mm) dataset was obtained from Fick and Hijmans [33]. The mean annual precipitation seasonality is calculated as the ratio of the standard deviation to the mean. Therefore, higher seasonality indicates higher differences in minimums and maximums. The dataset was obtained from the same authors [33]. The mean annual temperature (°C/10) is defined as the mean of the maximum and minimum temperatures of the hottest and the coldest months of the year. The mean annual temperature seasonality is calculated as the standard deviation of mean annual temperatures multiplied by 100. Therefore, higher seasonality indicates higher differences between minimums and maximums. Both temperature datasets were obtained from Fick and Hijman [33]. The average wind speed (m/s) is a scalar average defined as the mean of the wind magnitudes (speed), not considering the wind direction. The dataset used was developed by Davis et al. [34].

The distance to a main river dataset is available from the European Environment Agency [35]. Data are originally given in meters and was transformed to km. Elevation (m) is the altitude in relation to the sea level. The dataset was obtained from Copernicus [36]. The slope is defined as the steepness of the ground locally and is derived from the same dataset; the data are given in dN and were transformed to an angle measured in degrees through the equation $\text{degrees} = \arcsin(dN/250) \times 180/\pi$. The normalised difference vegetation index describes the contrast between visible and near-infrared reflectance of vegetation cover. The higher the index, the higher the vegetation cover. The dataset was obtained from Copernicus [37].

The sampling points were geographically referenced and entered into a geographical information system. Different layers of information for the variables considered were used to extract the values observed in the sampled points. The information about the existence of transhumance and the number of beehives in the apiary was obtained from the beekeepers. Data were then exported for an Excel sheet for further analysis.

The software used to collect these data was ArcGIS Pro version 3.2.1.

2.4. Data Analysis

Capture counts were conducted in different trap and attractant (bait) combinations: artisanal trap with artisanal bait, artisanal trap with commercial bait, commercial trap with artisanal bait, and commercial trap with commercial bait. The counts were grouped and recorded every 15 days from the start of the trial, in the second fortnight of February 2023 and until the second fortnight of August 2023.

An analysis of variance (ANOVA) is applied to each of the counting dates to establish any significant differences in the number of captures in each of the bait and trap combinations considered. The least significant difference (LSD) test was used as a post hoc. The prerequisites of the ANOVA were checked through Levine’s test and Q-Q plots, respectively, for the homogeneity of variances and normal distribution of the residuals. A graph of the temporal variation of captures was produced to visualise the data, using Microsoft® Excel®, version 16.88 (24081116).

The Poisson models for counts were fitted independently for each of the IVs using the number of captures in the first fortnight of April and in the first fortnight of September. These peaks correspond, respectively, to the maximum number of captures of primary workers and secondary workers. The models were fitted via the Generalized Linear Models routine. The omnibus test of the models was performed with a likelihood ratio chi-square test and the test of model effects was performed with a Wald chi-square test. The models' goodness of fit was evaluated using Akaike's Information Criterion (AIC). The models were fitted without intercept to facilitate interpretation.

The correlation tests were performed with Pearson's test after verifying that all the IVs have a normal distribution. The Kolmogorov–Smirnov test was used for that purpose. All the statistical analyses were performed with the software IBM® SPSS®, version 29.0.2.0 (20). The datasets were initially prepared using Microsoft® Excel® and then exported to SPSS.

3. Results

3.1. Differences in Captures between the Different Combinations of Trap and Attractant

The results of the ANOVA tests for significant differences between captures can be consulted in Table 1.

Table 1. Results of the ANOVA test of the quantities of Asian hornet captures in the different combinations of trap and attractant (bait), and in the different temporal intervals considered in the study.

Fortnight \ Trap/Bait	1	2	3	4	F Test p-Value
1 February	1.83	1.70	1.80	1.30	>0.05
2 February	4.67	4.77	4.80	4.20	>0.05
1 March	8.73	7.97	8.40	7.67	>0.05
2 March	18.67	17.93	17.87	16.90	>0.05
1 April	23.40	22.60	23.20	22.20	>0.05
2 April	14.27 ^a	16.77 ^b	14.47 ^a	16.17 ^b	>0.05
1 May	7.23	6.73	7.83	7.10	>0.05
2 May	3.23 ^{a,b}	3.03 ^a	4.30 ^c	3.90 ^{b,c}	>0.05
1 June	2.07	1.97	2.40	1.80	>0.05
2 June	7.13	6.63	7.97	7.37	>0.05
1 July	14.13	15.33	14.60	14.83	>0.05
2 July	32.17	31.27	29.97	30.33	>0.05
1 August	75.67	75.03	72.97	71.23	>0.05
2 August	114.43	112.20	112.87	109.93	>0.05

Note: 1—Commercial trap, commercial attractant; 2—Commercial trap, artisanal attractant; 3—Artisanal trap, commercial attractant; 4—Artisanal trap, artisanal attractant. In the fortnights where significant differences were found ($p < 0.5$), different letters in superscript are indicative of significant differences between captures in the different combinations of trap/attractant.

As can be observed, significant differences in the number of AHs captured can only be observed in the second fortnight of April and the second fortnight of May. In the former, the highest number of captures occurs in the combination of artisanal and/or commercial traps and artisanal bait, while in the latter, the largest captures are observed in combinations of artisanal traps and commercial and/or artisanal bait.

3.2. Temporal Variation of Captures

The temporal variations of captures can be observed in Figure 4. As can be observed, the first capture peak was reached at the beginning of April and corresponds to the peak of primary AH workers. It should be noted that the peak of captures of secondary workers had not yet been reached by the end of August when the trial was halted. As can also be observed, the added trend lines for the captures in the different combinations of trap and attractant are very coincident, indicating the lack of significant differences found in captures, in the different combinations of trap and attractant.

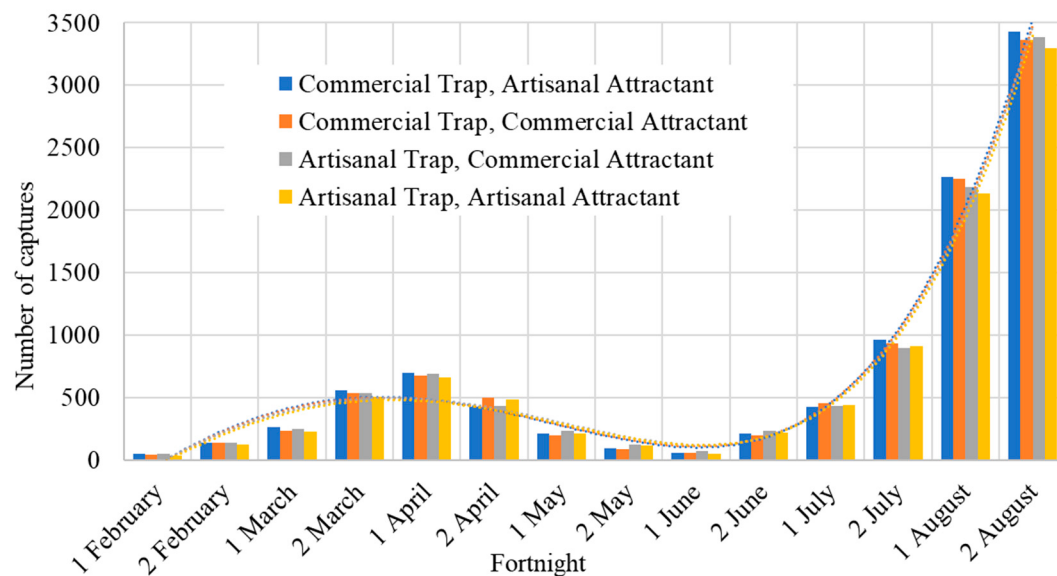


Figure 4. Temporal variation of Asian hornet captures in the different combinations of trap and attractant (bait). The trend lines are polynomials of degree 3.

3.3. The Influence of Human Factors, Geography, Climate, and Vegetation on Captures

The parameters of the univariable Poisson models fitted to the data are shown in Table 2. It is, however, important to underscore that the validity of these models applies only between the intervals observed for the minimum and maximum values of the independent variables (consult Table 3), as these are the values contained by the sample. Any other extrapolation for values outside the sampling values cannot be validated.

Table 2. Univariable Poisson models' parameterization using the two dependent variables, and the independent variables indicated. The p -values correspond to the significance of the model. The Akaike's Information Criterion for each of the models is also given. The models were fitted without intercept. β corresponds to the parameter and $\text{Exp}(\beta)$ corresponds to the odds ratio of the parameter. The level of significance of the parameter is given using the symbology near the value.

DV in the Model IV in the Model	Primary Workers				Secondary Workers			
	p -Value	AIC	β	$\text{Exp}(\beta)$	p -Value	AIC	β	$\text{Exp}(\beta)$
Ner of beehives	<0.001	11,399	0.058 ***	1.060	<0.001	82,827	0.075 ***	1.078
Albedo	<0.001	462	0.003 ***	1.003	<0.001	3095	0.004 ***	1.004
Aridity index	<0.001	477	3.444 ***	31.326	<0.001	2140	4.649 ***	104.464
Distance to a main river	<0.001	8323	0.412 ***	1.509	<0.001	60,074	0.539 ***	1.715
Elevation	<0.001	10,093	0.008 ***	1.008	<0.001	78,921	0.010 ***	1.010
Mean annual precipitation	<0.001	273	0.003 ***	1.003	<0.001	1292	0.004 ***	1.004
Precipitation seasonality	<0.001	253	0.900 ***	1.094	<0.001	647	0.122 ***	1.130
Mean annual temperature	<0.001	340	0.034 ***	1.034	<0.001	1200	0.046 ***	1.047
Temperature seasonality	<0.001	493	0.001 ***	1.001	<0.001	6098	0.001 ***	1.001
NDVI	<0.001	375	0.025 ***	1.025	<0.001	2222	0.034 ***	1.034
Population density	<0.001	15,129	0.09 ***	1.009	<0.001	108,247	0.012 ***	1.012
Slope	<0.001	4126	0.294 ***	1.342	<0.001	32,493	0.386 ***	1.471
Wind speed	<0.001	1359	0.738 ***	2.091	<0.001	11,346	0.983 ***	2.674

Note: Significance levels of the parameters in the models: *** $p < 0.001$.

Table 3. Descriptive statistics of the independent variables.

	N	Minimum	Maximum	Mean	Standard Deviation
Ner	30	1	100	33.830	28.122
A	30	1199.360	1692.380	1465.333	109.575
AI	30	1.091	1.420	1.291	0.096
DR	30	0.385	14.266	6.271	3.986
E	30	16.674	848.089	281.473	191.900
MP	30	1315.680	1446.880	1387.384	35.542
MPS	30	47.962	51.773	50.017	1.057
MT	30	116.157	140.953	132.790	7.398
MTS	30	3616.450	4668.230	4100.121	347.627
NDVI	30	147.664	195.797	180.142	10.265
PD	30	0.047	665.646	107.748	131.344
S	30	2.075	20.159	12.176	4.303
WS	30	3.922	7.549	5.704	0.912

Note: Ner—number of beehives, A—Albedo, AI—Aridity Index, DR—distance to a main river, E—elevation, MP—mean annual precipitation, MPS—mean annual precipitation seasonality, MT—mean annual temperature, MTS—mean annual temperature seasonality, NDVI—normalised difference vegetation index, PD—population density, S—slope, WS—wind speed.

The first impression taken from the models is that those fitted to the DV count of captures for primary workers (PWs) and those fitted to the DV count of captures for secondary workers (SWs) reiterate each other. The parameters of the models are all highly significant, with $p < 0.001$, all have the same direction (all positive), and as the number of captures for secondary workers is higher, the values of the parameters are higher as well in the respective models.

From the models we can infer that:

As the number of beehives in the apiary increases, so do the captures, at a rate of 7.5% per beehive. Albedo also positively affects captures, with rates increasing by 0.3% and 0.4% per unit for the Primary Workers Model (PWM) and the Secondary Workers Model (SWM), respectively. The number of captures increases with the aridity index, and thus with increased humidity or decreased evapotranspiration, by 344.4% for the PWM and 464.9% for the SWM. These high values are explained by the low variation in the sampled values observed, 1.091 and 1.420, respectively, for the minimum and maximum. Therefore, a variation of a centesimal part of the unit in the index results in increased capture rates of 3.444% and 4.649% for the PWM and SWM, respectively.

A greater distance from a main river leads to an increase in captures, with captures increasing by 50.9% and 71.5% per kilometre for the PWM and SWM, respectively. The number of captures also increases with elevation and slope, at rates of 0.08% and 0.1% per meter (for the PWM and SWM, respectively) for the former, and 29.4% and 38.6% per degree of slope angle (for the PWM and SWM, respectively) for the latter.

Captures increase with precipitation at rates of 0.03% and 0.04% (for the PWM and SWM, respectively) per accumulated millimetre. Higher precipitation seasonality also results in a greater number of captures, with rates of 109.4% and 113% for the PWM and SWM, respectively. Again, these high rates are due to the small variation in precipitation seasonality values in the samples (with a minimum of 47.962 and a maximum of 51.773).

Captures also increase with temperature, at rates of 3.4% and 4.6% (for the PWM and SWM, respectively) per accumulated degree. Higher temperature seasonality also results in an increased number of captures, with rates of 0.01% for both the PWM and SWM.

The Normalized Difference Vegetation Index (NDVI) positively influences the number of captures in both the PWM and the SWM, with rates increasing by 2.5% and 3.4% per index unit, respectively. The number of captures also increases with population density, at rates of 0.9% and 1.2% for the PWM and SWM, respectively, per person increase in population density. Finally, captures increase with mean wind speed, at rates of 209.1% and 267.4% for the PWM and SWM, respectively. These values should be interpreted

with caution, as the minimum and maximum values in the sample are 3.922 m/s and 7.549 m/s, respectively.

Some of the independent variables included in the models are correlated (see Table 4), and the effects on captures described may overshadow one another.

Table 4. Pearson’s correlation values between the independent variables considered in the study and respective levels of significance. Only the significant correlations are shown.

	Ner	A	AI	DR	E	MP	MPS	MT	MTS
DR			0.447 *						
E				0.471 **					
MP					0.449 *				
MPS			0.672 **		−0.431 *	−0.384 *			
MT	−0.370 *		0.662 **		−0.665 **	−0.434 *	0.800 **		
MTS			−0.801 **		0.540 **		−0.894 **	−0.903 **	
PD		0.418 *			−0.416 *				−0.367 *
WS			0.401 *	0.574 **				0.385 *	

Note: Ner—number of beehives, A—Albedo, AI—Aridity Index, DR—distance to a main river, E—elevation, MP—mean annual precipitation, MPS—mean annual precipitation seasonality, MT—mean annual temperature, MTS—mean annual temperature seasonality, PD—population density, WS—wind speed. Level of significance: * $p < 0.05$, ** $p < 0.01$.

Some easily explained correlations correspond to the increase in albedo with population density as in built environments the lack of vegetation conduces to an increased reflection of sunlight. The positive correlation between elevation and precipitation is also explained by increased condensation leading to precipitation, and the negative correlation with temperature is common knowledge. The negative correlation between elevation and population density is also evident as villages and cities in the region are in lowland areas. The negative correlation between precipitation and temperature is also explained by the fact that precipitation increases with elevation and, therefore, with decreasing temperatures.

4. Discussion

In our study, different combinations of commercial and artisanal traps and attractants (baits) were tested. It appears that there are marginal differences in only two of the fourteen fortnights with observations. Interestingly, in these two weeks where significant differences can be observed, combinations that contain artisanal devices have some advantage, showing a larger number of captures. It is considered, however, that this difference may be circumstantial and that there are no differences between the capture devices and baits.

In a study comparing the trappability of the AH, Lioy et al. [38] found that in the Spring, a simple artisanal attractant (beer) was more effective in the capture of the wasp than a commercial attractant (VespaCatch). They have also found that during Autumn, both the artisanal and commercial attractants have decreased their trappability, except the commercial bait when used with traps recommended by the fabricator. Such results suggest seasonal differences in catches, but also an attractant and a trap effect in the Autumn. The decrease observed in the Autumn is explained by the composition of both attractants based on sugar, as in the Autumn the secondary workers follow a protein-rich diet and increase their predation activity. In our study, and despite the lack of significant differences between the commercial and artisanal attractants in both seasons and both types of traps, the effectiveness was maintained during the later stages of the AH life cycle, when they followed a protein-based diet.

In another study testing the trappability of queen AHs (foundresses in the early stages of the cycle) using blackcurrant beer and honey beer, implemented in France [28], no significant differences were found between the attractants, but some effectiveness in trapping queens was observed, however, at the cost of other invertebrates also attracted to the traps. This lack of specificity of the attractants and traps has also been reported by other authors (e.g., Refs. [39,40]) and has been identified as a major problem as the number

of AHs captured accounts for around 1% of the total number of invertebrates captured (insects and arachnids, mainly). In our study, we did not produce any statistics for the number of other invertebrates captured; however, it was reported that a large number kept being attracted and captured in conjunction with the AH, including honeybees.

The development of different types of attractants more specific to the species must be found. Pheromones have been reported as a potential alternative. Wen et al. [41] reported the sensitivity of males to sex pheromones produced by virgin gynes (the reproductive AH females) and identified the exact compound produced in the sixth intersegmental sternal glands of the virgin gynes' abdomens as 4-oxo-decanoic acid that once synthesised artificially worked well. Other scientists such as Cheng et al. [42] and Dong et al. [43] have been exploring the composition of these pheromones and have also concluded the usefulness of these pheromones for attracting males of the AH, but also, however, from other wasp species. The peaks of captures observed in our study, coincident with the life cycle peaks of the AH in the Spring (primary workers) and later in the cycle in the Autumn (secondary workers), were also reported by different authors (e.g., Refs. [16,44–46]).

Under current circumstances, investment in the commercial equipment tested (traps and baits) is not recommended, should artisanal production be possible, as this option is the most economical. While other capture forms are studied, using traps with attractants remains a practical alternative. Despite its limitations in the control of invasive AHs, trapping remains an effective measure to monitor the presence and spread of the species. In addition, the trapping of AHs may persist as a useful method to study the ecological aspects of the species' dispersion. For this purpose, we have used the number of captured AH to evaluate their most suitable ecology.

The increase in captures with the increase in the number of beehives is obviously justified by the AH's predatory behaviour directed at the honeybee. The hornet's hunting behaviour is closely tied to the availability of its prey, particularly in regions where bee-keeping is prevalent. Several studies (e.g., Refs. [16,44–46]) highlight the direct impact of AHs on honeybee populations, showing how the presence of more beehives can attract more hornets due to the increased food supply, especially during the summer months when the needs of the colonies in protein increase to feed their larvae [44,47].

The positive effect of albedo on the captures of Asian hornets suggests that areas with higher reflectivity might influence the hornet's behaviour, possibly by affecting the thermal conditions of the environment. Although direct studies linking albedo to hornet activity are scarce, the influence of surface reflectivity on microclimate conditions could be a factor, as suggested in broader ecological studies on insect behaviour by Oke [48]. Another important fact related to albedo is the lack of dense vegetation in the immediate surroundings of the apiaries that may facilitate the predation activity of the AH. Nevertheless, NDVI positively influences hornet captures, likely due to the association between healthy vegetation and the availability of prey. This result corroborates that of Bessa et al. [49]. The authors explain this influence with the distribution of the AH's prey spectrum, including honeybees and other wasps. Areas with higher levels of vegetation provide abundant food resources [50,51] and suitable conditions for nesting [22,44].

Precipitation and its seasonality play a crucial role in the availability of resources and the establishment of hornet populations. Higher precipitation supports lush vegetation and insect populations, as discussed in the previous paragraph. The increase in captures with the aridity index is also linked to how this index affects the availability of water resources and vegetation.

The positive correlation between elevation, slope, and captures suggests that AHs might find certain elevations and sloped terrains more conducive to nesting and hunting. Hornets are known to exploit varied terrains for nesting sites, which can affect their spatial distribution [52]. Elevation is positively correlated with precipitation which was found to correlate with the number of captures. A study conducted by Herrera et al. [52] has also found steeper slopes as most suitable for AH nesting. The number of captures increases

as the distance from the main rivers increases. The most intuitive explanation for this relationship is the positive correlation between distance from the main rivers and elevation.

Temperature, particularly its seasonal variations, strongly influences the behaviour and distribution of AHs. Warmer temperatures generally promote higher metabolic rates and more active foraging. The AH's range expansion has been linked to regions with increased (more favourable) thermal conditions in Southern Germany [53] which has a summer range of temperatures like those observed in the Alto-Minho region of Portugal [54].

The increase in captures with population density is likely due to the proximity of human activities, such as beekeeping, which provides abundant food resources for hornets. Studies have shown that the AH tends to thrive in anthropogenic landscapes where beekeeping is common [53]. However, increased human activity, urbanisation, and population density are associated with lower albedo than those observed in forests and natural landscapes [55], which according to the previous discussion could result in a lower number of captures.

Higher wind speeds may facilitate the spread of AHs, aiding in the dispersal of hornets over larger areas and potentially increasing their encounter rates with prey. Nevertheless, Monceau et al. [44] found that increased wind speeds correlate negatively with predation once it interferes with the stationary flight of the AH needed to catch the honeybees.

In terms of limitations in the present study, the results discussed concerning the ecology of the AH in the Alto-Minho region of Portugal must be read with attention in consideration of the sample limits of the present study and should not be immediately transposed to other ecological contexts. Another important limitation of the study is the lack of quantification and identification of other species also captured in the traps. An important aspect in the evaluation of invertebrate traps is their selectivity for the targeted species. In the present study, such an evaluation was not possible as due to a restriction of human resources we relied on the beekeepers to count the number of captures of AHs only as these are not trained to identify other species with the necessary accuracy.

5. Conclusions

In this study, the effectiveness of various commercial and artisanal traps and attractants for capturing Asian hornets (AHs) was evaluated across different seasons. The results indicate that there were no significant overall distinctions between the effectiveness of commercial and artisanal attractants tested. The research highlights the influence of environmental factors, such as vegetation, elevation, and albedo, on AH captures, suggesting that these variables may play a role in the hornet's nesting and hunting behaviours. The study underscores the importance of considering seasonal variations, particularly concerning the hornets' dietary shifts, when assessing trap effectiveness. Although the tested commercial traps were not found to be significantly more effective, the study suggests that artisanal traps could be a more cost-effective alternative. The findings also emphasize the potential need for more specific attractants to reduce the unintended capture of non-target invertebrates, with pheromones being a promising avenue for future research.

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