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What drives the risk of being bitten by a viper? A fine spatial scale study in western France

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CRediT Author statement

Gaël Le Roux: Conceptualization, Methodology, Investigation, Writing – Original draft preparation. **Mickaël Guillon:** Software, Methodology. **Lise Bernard:** Investigation, Data curation. **Luc de Haro:** Writing – Review & Editing. **Olivier Lourdais:** Conceptualization, Methodology, Validation, Writing – Review & Editing. **Alexis Descatha:** Writing – Review & Editing, Supervision.

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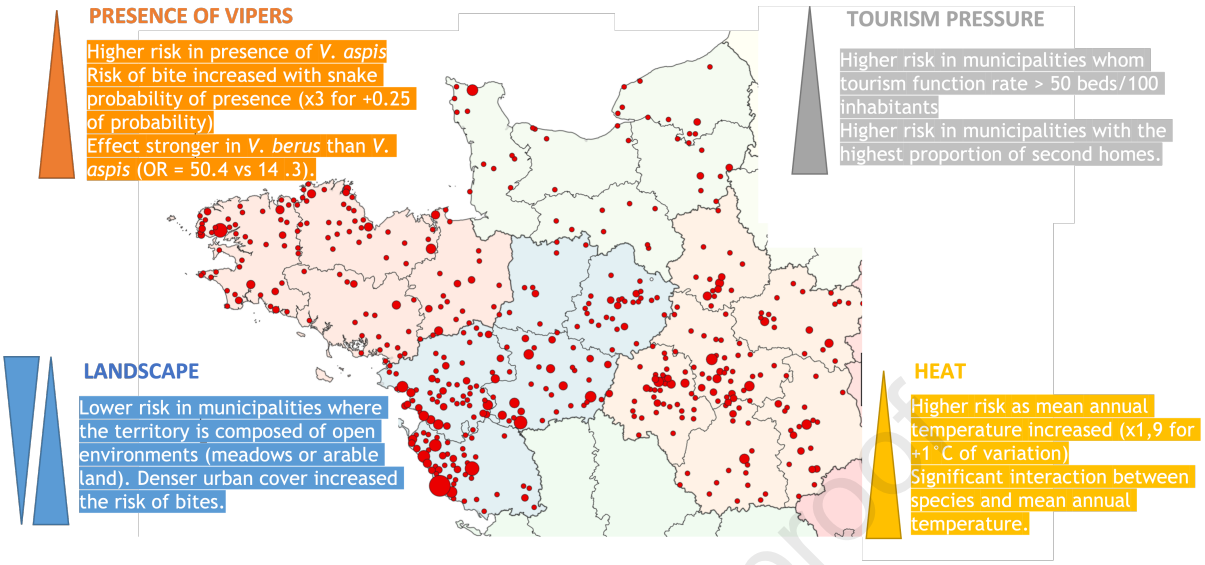
What drives the risk of being bitten by Vipers in France?



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Abstract

Previous studies on viper bites in France have focused on clinical consequences of envenomation, efficacy of antivenom and epidemiology of bites. Herein, we wanted to clarify temporal and spatial patterns in bite incidence using a fine spatial scale (municipality level). We focused on viper bites recorded over the last 10 years in 4 regions of western France. We addressed the determinants of bite occurrence and number of bites considering the following variables: predicted probability of viper presence, species (*V. aspis* or *V. berus*), climatic data, tourism function rate, soil transformation and landscape use. 703 bite cases were retained with significant disparities between areas. Bites occurred either during a garden-related activity (339 cases, 51.2%) or during an activity in the countryside (300 cases, 45.3%). The probability of presence of a viper at the municipality level positively influenced the risk of being bitten (multiplied by 3 for a variation in probability of 0.25 from 0.5) but varied between species (lower in *V. berus* than *V. aspis*). Artificial land development had a positive effect on bite risks. Finally, a tourism function rate above 50 beds/100 inhabitants was strongly associated with an increase in the risk of occurrence and frequency of bites. Overall, viper bites recorded in our study were concentrated on the south coastline of Pays de la Loire region. The coastal towns are significant areas of tourist attraction and are located close to preserved semi-natural landscapes that provide favorable habitats for vipers. This convergence may favor human/wildlife encounters.

Keywords: european viper; asp viper; snakebite; risk evaluation; tourism pressure

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1. Introduction

Viper bites in Europe are rare events with an overall incidence of 1.06 per 100,000 inhabitants (Chippaux, 2012). The associated burden and economic cost are much lower than in rural areas of developing countries (Africa, South East Asia, South America) (*Global snakebite burden*, 2018; Patikorn et al., 2020). According to a 2012 literature review, in Europe, rural activity was also a source of bites until the beginning of the 20th century, as illustrated by the number of viper hunters in the French, British and Italian countryside (Bronckers, 2020; Chippaux, 2012; Fabien, 1947). After the WWII in France, the shift in farming practices involving mechanization, pesticide intrants and single-crop production, have fundamentally altered natural habitats, contributed to the loss of biodiversity and led to the rarefaction of human/animal encounters (European Commission, 2001). Today, the development of nature-related activities (hiking, fishing, etc.) and tourism in rural areas has changed the circumstances in which people are bitten, the age groups concerned (children), as well as the seasonality of bites (late spring and summer) (Chippaux, 2012).

Heretofore, most epidemiological studies focus only on identifying individual risk factors without addressing other relevant aspects related to snake ecology or anthropic pressure on natural habitats (Murray et al., 2020). Patterns of spatial variation in bite incidence at a fine scale are, by contrast, rare and relatively new. There are a few examples, notably in Sri Lanka (Ediriweera et al., 2018; Goldstein et al., 2021), in Costa Rica (Bravo-Vega et al., 2019), in Bangladesh (Rahman et al., 2010) or in Iran (Yousefi et al., 2020). Most of them assume that the distribution of bites is mainly related to the overlap of snake and human activities. Some studies have successfully developed a mechanistic approach applying to snakebites methods used in determining the risk of zoonotic spread (Martín et al., 2022). For example, snake distribution and abundance models and human population density maps could be used to represent the human-snake spatial alignment that underlies human-snake contact (Martín et al., 2022). Species distribution (SDM) modeling permit to clarify environmental determinant of species presence (Sillero et al., 2021) and their spatial output can provide relevant tools in spatially explicit epidemiological studies.

Metropolitan France is home to four species of viper: *Vipera aspis* (asp viper), *Vipera berus* (common European adder or adder), *Vipera seoanei* (Seoane's viper) and *Vipera ursinii* (Orsini's viper, meadow viper). The latter two have an extremely limited range in France and hardly aggressive (no significant envenomation has been reported with *V. ursinii* (Orsini et al., 1998)). Western Palearctic vipers (Genus *Vipera*) typically have a parapatric distribution with reduced contact zone. Broadly speaking, the Loire valley is the limit of distribution for *Vipera aspis* in the north-west and for *Vipera berus* in the south. A very narrow contact zone occurs notably in Loire Atlantique (Guiller et al., n.d.). While hybridization is possible, the phenomenon is very rare with limited gene flow between the species (Guiller et al., 2017; Zwahlen et al., 2022).

These two main species are responsible for 200 to 300 bites each year in France, with large disparities between regions. The studies carried out on vipers in France have focused on the clinical consequences of envenomation, the efficacy of antivenom and the epidemiology of bites (Boels et al., 2009; de Haro, 2012; De Haro et al., 2002; Jollivet et al., 2015).

The aim of the present study is to apply this reasoning to venomous snake bites in the north-western quarter of France, a region particularly exposed to viper envenomation. We examined the following hypothesis: (1) First, we posit that bite risks should be driven by environmental factors including seasons, with higher occurrence in summer (which correspond to viper activity period); (2) Second, bite risks should be increased by human activities and notably summer tourism that should favor the probability of encounters; (3) Third, we also hypothesized that land transformation should influence snake bite leading to an overlap between the high probability of presence of vipers and the perimeter of human activity.

2. Methods

2.1. Study area and species occurrence

The study area includes four regions (Normandy, Brittany, Pays de la Loire, Centre-Val de Loire regions) that correspond to the area of competence of the Grand Ouest Poison Control Center (PCC). This study area is ecologically relevant since in encompass the distribution limits of the two most widespread vipers in France, the adder *(V. berus)* and the aspic viper *(V. aspis).* The ecology of the species has been intensely studied in Western France and notably their ecophysiology, reproduction, and conservation (Dezetter et al., 2021; Guiller et al., 2012; Guillon et al., 2014; Lourdais et al., 2013). Both species are facing important decline because of habitat degradation (Guiller et al., 2022; Reading et al., 2010).

2.2. Case selection and information

All cases were extracted from the French National Poisoning Cases Database, which is fed by the daily calls received by the 8 French PCCs. All cases of bites in the area of competence of the Grand Ouest PCC (Normandy, Brittany, Pays de la Loire, Centre-Val de Loire regions) were included, whenever the imputability of a viper was considered very probable or probable, according to the following criteria:

(a) Very probable: presence of one or two points of skin puncture compatible with a viper bite (hand up to the wrist, foot up to the ankle) with signs of envenomation such as local oedema, pain, bleeding from the skin puncture.

(b) Probable: in case of lesions of doubtful aspect, observation of a viper (identified as such by the toxicologist) in the immediate vicinity of the victim.

This selective approach was important since other type of bites or small wounds can be mistakenly attributed to vipers by the public because of a lack of knowledge. The species involved in the bite is only accessible in very rare cases (sufficiently clear photo of the animal, the killing of the animal, etc.).

The date and location of bites and the activity at the time of the bite were the only data collected for the study. When known, the municipality where the bite occurred was the elementary unit of space. Failing that, it was the commune where the nearest distributing post office (identified by its postal code) was located. If no bite location was indicated, the commune of the hospital where the patient was treated was considered. Because bite data are retrospective they may be overclouded by approximations, particularly regarding their exact location. The communal unit is the most detailed information that can legitimately be expected from a telephone response to an emergency.

The activity at the time of the bite was categorized into four types:

(1) activity in a wilderness area (hiking, climbing, swimming, etc.),
(2) activity in a private or public garden (gardening, mowing the lawn, etc.),
(3) activity on the public path (on the street, on the roadside, etc.),
(4) activity in another type of place or unknown.

The biting circumstance was considered with three categories:

(1) voluntary when it resulted from a voluntary interaction with the animal (attempt to catch, kill, handle),
(2) professional when it occurred during the victim's professional activity.
(3) accidental (all other cases).

2.3. Explanatory variables considered

2.3.1. Viper occurrence

The probability of occurrence of vipers was determined in a previous work, based on correlative models of species distribution (Guillon, 2012) using occurrence data at the municipality level gathered over the last 30 years by the French herpetological society (SHF) from regional conservation organizations and herpetologists' observations . The correlative models use relationships between field observations (occurrence), and climatic variables to project the realized niche. Environmental variable used included temperature and precipitation data (AURELHY, METEO-FRANCE corresponding to the 1971-2000 period) and monthly interpolated solar irradiation database (PVGIS © European Communities). Spatial projections were obtained for the probability of the presence of *V. berus* (the adder) and *V. aspis* (the asp

viper). The accurate determination of the species involved in the bite is difficult to obtain notably because the two species are quite similar. Therefore, we determined the species involved at the site from the highest probability of presence. In the Pays de la Loire and Centre-Val de Loire regions *V. aspis* was the most frequent species (76.1% and 86.3% of communes respectively) and the average presence probability of *V. aspis* was 0.55 and 0.46 respectively. In turn *V. berus* was dominant in Normandy and Brittany (in 99.7% and 97% of the municipalities respectively). Its probability of presence was 0.51 and 0.63, respectively.

2.3.2. Climatic conditions

The meteorological data were extracted from the International Surface Synoptic Observations (SYNOP) circulating on the World Meteorological Organisation (WMO) Global Telecommunication System (GTS) (Météo-France, n.d.). The data extracted were daily minimum, maximum and mean temperatures, and daily sunshine duration in hours. Sunshine's duration is the time during which a location is subject to effective insolation, i.e. sufficient solar radiation to produce distinct shadows. A total of 27 SYNOP stations were used. The data was not available for all the municipalities in the area. Therefore, each municipality was assigned the climate data of the nearest SYNOP station. The average distance between a municipality and the nearest station was 31.52 km.

2.3.3. Landscape attributes

As a first approach, the artificial modification of land variable was used. This is a public data produced by the French Observatory for Soil Artificialization which reflects the transformation of natural, agricultural and forestry areas by urban or industrial development operations (Cerema, n.d.).

The land cover at the local level was obtained from CORINE Land Cover (CLC)("CORINE Land Cover," 2018). This is a biophysical inventory of land cover and its evolution according to a 44-item nomenclature. This inventory is produced by visual interpretation of satellite images. The production scale is 1:100,000. CLC is used to map homogeneous land use units with a minimum surface area of 25 ha. The latest version (2018) was used with the following land-use items: 111, continuous urban fabric; 112, discontinuous urban fabric; 12, industrial, commercial and transport units; 13, mine, dump and construction sites; 14, artificial, non-agricultural vegetated areas; 21, arable land; 22, permanent crops; 23, pastures; 24, heterogeneous agricultural areas; 32, scrub or herbaceous vegetation associations; 33, open spaces with little or no vegetation; 4, wetlands; 5, waters. The amount of each item was related to the area of the municipality.

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2.3.4. Demographic data

The data on resident population and communal area are taken from the National Institute of Statistics and Economic Studies (INSEE), the public agency responsible for the production, analysis, and publication of official statistics in France (Institut National de la Statistique et des Etudes Economiques, 2021).

The communal density grid is a variable that characterizes municipalities according to the distribution of their population in their territory. Thus, the more concentrated and numerous the population is, the denser the municipality is considered to be. In addition to the three levels of density defined at European level (densely populated municipalities, intermediary density municipalities and rural municipalities), France has divided the so-called rural municipalities into sparsely populated and very sparsely populated municipalities, in order to refine the description of sparsely populated territories (Institut National de la Statistique et des Etudes Economiques, 2022).

2.3.5. Tourism intensity

The tourism variables are calculated based on the number of tourist beds offered by each municipality, which is public data produced by INSEE.

The tourist function rate is the ratio between the tourist accommodation capacity of municipalities (number of tourist beds) and their year-round resident population. It is an indicator of tourist pressure that makes it possible to quantify the theoretical multiplication of the population in periods of tourist influx. For example, a municipality with a tourist function rate of 100 beds per 100 inhabitants will be able to welcome as many visitors as it has permanent inhabitants. The tourist density is a complementary variable, expressed as the number of tourist beds per km2. We also considered the share of second homes in the housing stock of each commune. This is also public data produced by INSEE.

2.4. Statistics

The statistics were carried out using R software (R version 4.0.3). We first considered the occurrence, per municipality, of at least one bite (0/1) in 10 years. We also considered the total number of bites per municipality over the same period

2.4.1. Univariate Analysis

Quantitative variables are reported as mean (SD). We performed Fisher's exact test or Pearson's Chi-squared test as allowed by the conditions of application. Qualitative data (activity and circumstances, location and date of bite, viper species) and categorical variables were expressed as n (%). We analysed them using Welch Two Sample t-test.

2.4.2. Bite occurrence models

We used a logistic regression to determine the variables influencing the occurrence of at least one bite in each municipality. The variables defined a priori according to the literature data (probability of viper presence, viper species, average annual temperature, tourism function rate and soil transformation) were introduced in the first model.

The search for other potential adjustment variables involved a second penalized regression model of the LASSO (Least About Shrinkage and Selection Operation) (R-package 'glmnet'). The penalty coefficient (lambda) was chosen to provide an estimation error of less than one standard deviation from the minimum error obtained by 10-fold cross-validation, while being as parsimonious as possible. We kept the variables that had a coefficient different from 0 with this lambda coefficient. Finally, an approach using a backward and forward stepwise algorithm was also used, based on a full logistic model, and after deleting multicollinear variables (variance inflation factor > 5). The quality of the models was assessed by their AIC and BIC index, the deviance, estimated by the pseudo-R2 (rate of variance explained by the model), the error rate of the model after performing a confusion matrix (threshold of probability of bite at 0.5), as well as the AUC of the corresponding ROC curve.

2.4.3. Bite number models

As bites are rare events but for which regional disparities exist, it is necessary to check the absence of overdispersion of the data and to take into account a number of zero observations that is much higher than what the Poisson distribution would suggest. We used Zero-inflated Negative binomial and Negative binomial hurdle models were each fit to the data with general linear regression (R-packages 'AER', 'MASS' and 'pscl'). The dependent variable was the count of bites in 10 years. Independent variables were those that have been used for the binomial logistic regression. We used the same predictors both in the count part and the logit part of the zero-inflated models.

Various statistical tests were applied to evaluate over-dispersion and compare model fit. For negative binomial models, the dispersion parameters were tested for difference from zero with t-statistics. To assess the goodness-of-fit of models, likelihood and AIC were determined.

3. Results

3.1. Descriptive analysis

Over the study period (January 2012 to May 2021), 703 bite cases were recorded in 488 municpalities of the four regions covered (Figure 1). The Pays de la Loire region was the region with the highest number of bites (41.8%, 294 cases), followed by the Centre-Val de Loire region

(28.0%, 197 cases), Brittany (22.9%, 161 cases) and finally, Normandy (7.3%, 51 cases). This change was significant (p<0.001).

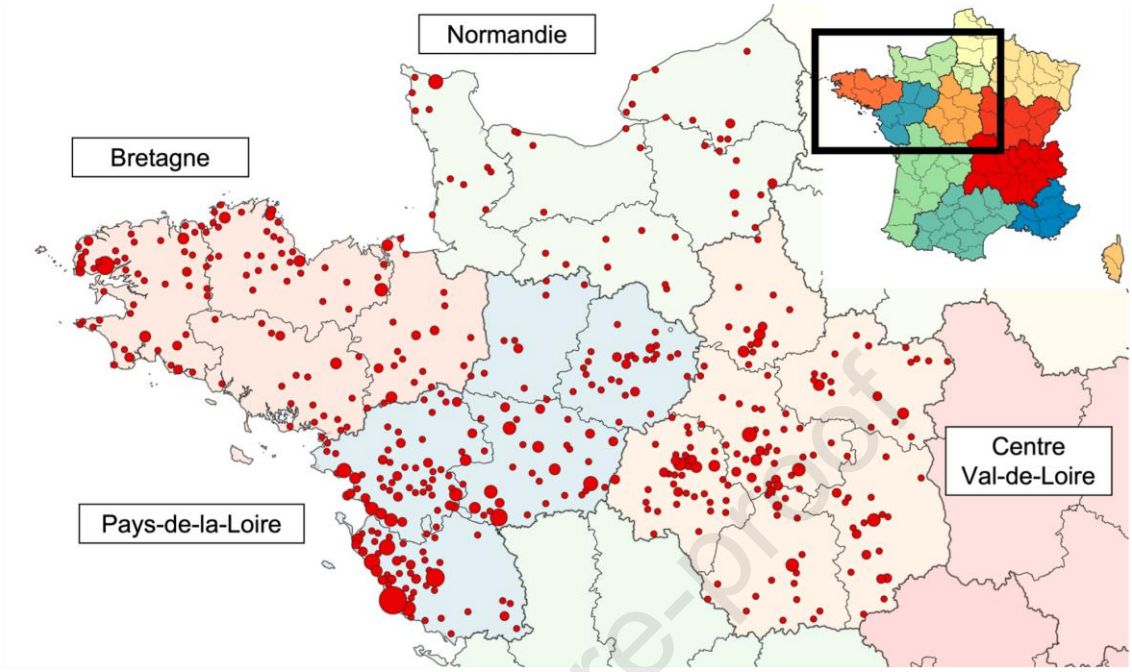

Figure 1. Study area and location of bite cases. Each circle corresponds to a municipality where at least one bite was observed. The area of the circle corresponds to the number of bites observed.

An important disparity was observed in the number of bites, which reached 18 in one municipality of the Vendée coast. The observed mean of the number of bites was 0.102, while the observed variance was 0.240, indicating an overdispersion of the data, confirmed by a dispersion test (z = 3.6332, p-value <0.0001). To explore the excess of null observations, we visually examined the data. The Poisson distribution underestimates the null observations and overestimates the number of communes with a single bite.

3.2. Bite circumstances

Bites occurred mainly in the second and third quarters (660 cases, 93.9%, p=0.0016), with a maximum in July (162 cases). During the day, 92.7% of bites (652 cases) occurred between 8:00 a.m. and 9:00 p.m., with 41.4% (270 cases) occurring between 3:00 p.m. and 6:00 p.m.

The bites either occurred during a garden-related activity (339 cases, 51.2%) or during an activity in the countryside (300 cases, 45.3%). Seven cases occurred on the public road. For the other cases (57 cases, 8.1%), the location or activity was unknown.

The majority of bites (502 cases, 75.8%) were the result of a fortuitous encounter with the animal. Only fifty-one patients (7.7%) were bitten while attempting to interact with the animal (e.g., to catch it, to photograph it). There was no significant difference between the two species regarding

the circumstances of bites (p<0.9). However, bites in the contryside were significantly more frequently associated with *V. berus* than with *V. aspis* (55.4% vs. 42.7%, p=0.0314).

3.3. Probability of being bitten at municipal level

The occurrence of a bite in the municipalities according to species characteristics, climate, resident and tourist population and land use is described in Table 1.

Table 1. Features of the municipalities in terms of species data, climate, tourist and resident population and land use, according to the occurrence or not of at least 1 bite in 10 years (OR: odd ratio, Ref: variable level take as reference). There are 6852 municipalities in the region of interest, of which 488 had 703 bites.

Number of bites in the municipality in 10 years	**None, N = 6364**	**At least one bite, N = 488**	**OR (95% CI)**	**p**
Viper species				<0.001
Vipera berus	4,166 (65%)	185 (38%)	Ref.	Ref.
Vipera aspis	2,198 (35%)	303 (62%)	3.10 (2.57-3.76)	<0.001
Probability of viper presence	0.52 (0.13)	0.57 (0.13)	21.41 (10.29-44.89)	<0.001
Average daily sunshine duration (h)	5.02 (0.44)	5.25 (0.46)	3.58 (2.84-4.55)	<0.001
Average annual sunshine duration (h)	1,744.92 (150.90)	1,825.38 (154.14)	1.00 (1.00-1.00)	<0.001
Average annual temperature (°C)	11.79 (0.56)	12.21 (0.52)	3.88 (3.26-4.64)	<0.001
Annual average minimum temperature (°C)	7.69 (0.56)	8.01 (0.65)	2.82 (2.37-3.37)	<0.001
Annual average maximum temperature (°C)	16.59 (0.90)	17.11 (0.89)	2.04 (1.81-2.30)	<0.001
Tourist density (number of beds/km2)				<0.001
≤ 10	5,744 (90%)	331 (68%)	Ref.	Ref.
11 – 20	174 (2.7%)	38 (7.8%)	3.79 (2.59-5.42)	<0.001
21 – 50	217 (3.4%)	59 (12%)	4.72 (3.44-6.38)	<0.001
51 – 100	90 (1.4%)	24 (4.9%)	4.63 (2.85-7.24)	<0.001
> 100	137 (2.2%)	36 (7.4%)	4.56 (3.07-6.62)	<0.001
Tourism function rate (number of beds/100 inhabitants)				<0.001
< 50	6,170 (97%)	449 (92%)	Ref.	Ref.
50 – 99	103 (1.6%)	17 (3.5%)	2.27 (1.30-3.72)	0.002
100 – 199	67 (1.1%)	15 (3.1%)	3.08 (1.68-5.28)	<0.001
≥ 200	22 (0.3%)	7 (1.4%)	4.37 (1.72-9.80)	<0.001
Percentage of secondary residences	11.53 (11.39)	11.59 (14.37)	1.00 (0.99-1.01)	>0.9
Communal density scale				<0.001
High density	59 (0.9%)	25 (5.1%)	Ref.	Ref.
Medium density	431 (6.8%)	100 (20%)	0.55 (0.33-0.93)	0.022
Low density	4,434 (70%)	324 (66%)	0.17 (0.11-0.28)	<0.001
Very low density	1,439 (23%)	39 (8.0%)	0.06 (0.04-0.11)	<0.001
Artificial development of land (% of municipal area)				<0.001
< 1%	1,847 (29%)	35 (7.2%)	Ref.	Ref.
1 – 4%	2,176 (34%)	167 (34%)	4.05 (2.84-5.95)	<0.001
5 – 9%	1,186 (19%)	96 (20%)	4.27 (2.91-6.41	<0.001
10 – 49%	1,055 (17%)	152 (31%)	7.60 (5.29-11.23	<0.001
≥ 50%	99 (1.6%)	38 (7.8%)	20.26 (12.27-33.58)	<0.001
Continuous urban fabric				<0.001

< 1%	6,328 (99%)	440 (90%)	Ref.	Ref.
≥ 1%	36 (0.6%)	48 (9.8%)	19.18 (12.35-30.04)	<0.001
Heterogeneous agricultural areas				<0.001
< 25%	5,078 (80%)	322 (66%)	Ref.	Ref.
25 – 49%	1,078 (17%)	145 (30%)	2.12 (1.72-2.60)	<0.001
≥ 50%	208 (3.3%)	21 (4.3%)	1.59 (0.97-2.47)	0.049
Industrial, commercial and transport units				<0.001
< 5%	6,022 (95%)	396 (81%)	Ref.	Ref.
≥ 5%	342 (5.4%)	92 (19%)	4.09 (3.17-5.24)	
Arable land				<0.001
< 25%	1,645 (26%)	199 (41%)	Ref.	Ref.
25 – 49%	2,014 (32%)	170 (35%)	0.70 (0.56-0.86)	<0.001
≥ 50%	2,705 (43%)	119 (24%)	0.36 (0.29-0.46)	<0.001
Pastures				<0.001
< 25%	4,147 (65%)	389 (80%)	Ref.	Ref.
25 – 49%	1,392 (22%)	75 (15%)	0.57 (0.44-0.74)	<0.001
≥ 50%	825 (13%)	24 (4.9%)	0.31 (0.20-0.46)	<0.001
Discontinuous urban fabric				<0.001
< 10%	5,352 (84%)	304 (62%)	Ref.	Ref.
10 – 24%	772 (12%)	117 (24%)	2.67 (2.12-3.34)	<0.001
25 – 49%	184 (2.9%)	53 (11%)	5.07 (3.63-6.98)	<0.001
≥ 50%	56 (0.9%)	14 (2.9%)	4.40 (2.33-7.77)	<0.001
Artificial, non-agricultural vegetated areas				<0.001
< 5%	6,256 (98%)	466 (95%)	Ref.	Ref.
≥ 5%	108 (1.7%)	22 (4.5%)	2.73 (1.67-4.28)	<0.001
Mine, dump and construction sites				0.035
< 1%	6,090 (96%)	457 (94%)	Ref.	Ref.
≥ 1%	274 (4.3%)	31 (6.4%)	1.51 (1.01-2.18)	0.035
Permanent crops				<0.001
< 5%	6,206 (98%)	450 (92%)	Ref.	Ref.
≥ 5%	158 (2.5%)	38 (7.8%)	3.32 (2.27-4.73)	<0.001
Scrub and/or herbaceous vegetation associations				<0.001
< 5%	6,123 (96%)	454 (93%)	Ref.	Ref.
≥ 5%	241 (3.8%)	34 (7.0%)	1.90 (1.29-2.72	<0.001
Open spaces with little or no vegetation				>0.9
< 0.5%	6,357 (100%)	488 (100%)		
≥ 0.5%	7 (0.1%)	0 (0%)		
Wetlands				<0.001
< 5%	6,159 (97%)	445 (91%)	Ref.	Ref.
≥ 5%	205 (3.2%)	43 (8.8%)	2.90 (2.04-4.05	<0.001
Waters				0.002
< 5%	6,148 (97%)	458 (94%)	Ref.	Ref.
≥ 5%	216 (3.4%)	30 (6.1%)	1.86 (1.23-2.72)	0.002

A first a priori model (model 0) was run to determine the variables that significantly affect the risk of at least one bite occurring in the period considered (see Supplementary Material 1). We also introduced a first notion of land use represented by the artificial transformation of the soils. It was found significantly ($p<0.001$) that as the proportion of degraded land in the municipality increased, so did the risk of at least one bite occurring there. The effect of the model 0 variables on the predicted probability of bite is summarized in Figure 2.

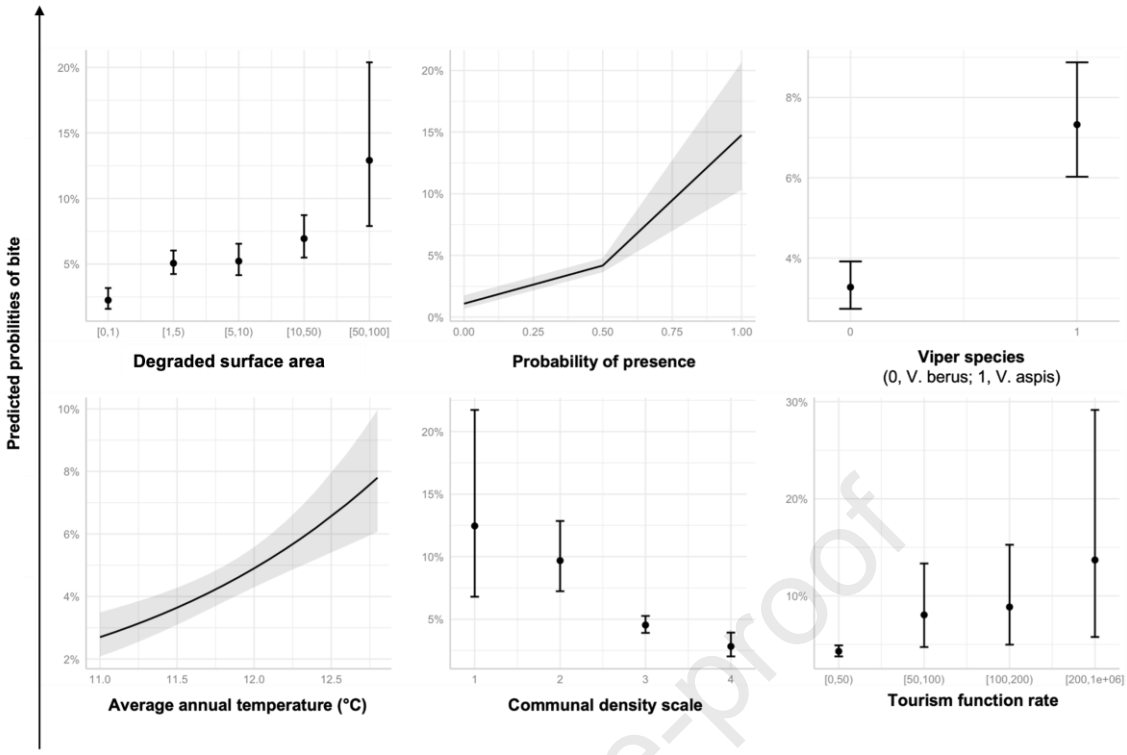

Figure 2. Effect of model 0 variables (a priori) on the predicted probability of bite, in 10 years.

An a priori model (model 1) with the detailed land-use items (according to CLC) and the search for complementary explanatory variables by a LASSO type model (model 2) and a model based on a selection algorithm (model 3) were carried out (see Supplementary Material 1). We also introduced land use variables in model 1, namely the part of continuous urban fabric and the part of heterogeneous agricultural environment. Models 2 and 3 also retained these variables, while identifying others (part of discontinuous urban fabric and arable land).

Given the OR value of the species variable, we analyzed two data subgroups corresponding to the two species. On each of these data subgroups, we applied an a priori model, using the variables of model 0 (Figure 3). The risk of being bitten increased with snake probability of presence but the effect was stronger in *V. berus* than *V. aspis* (OR = 50.4 vs 14.3). The ORs are similar for the communal density grid and artificial development of land variables. However, there was a difference between the two species for the mean annual temperature variable, with the OR being significantly different from 1 (2.86) only for *V. berus.* We confirmed that by demonstrating a significant interaction ($p<0.001$) between the species variable and annual mean temperature in model 0 (OR=0.34) (Figure 4). Finally, the tourist function rate does not seem to significantly influence the risk of being bitten by *V. berus*, whereas its increase is a favourable factor in the case of *V. aspis*.

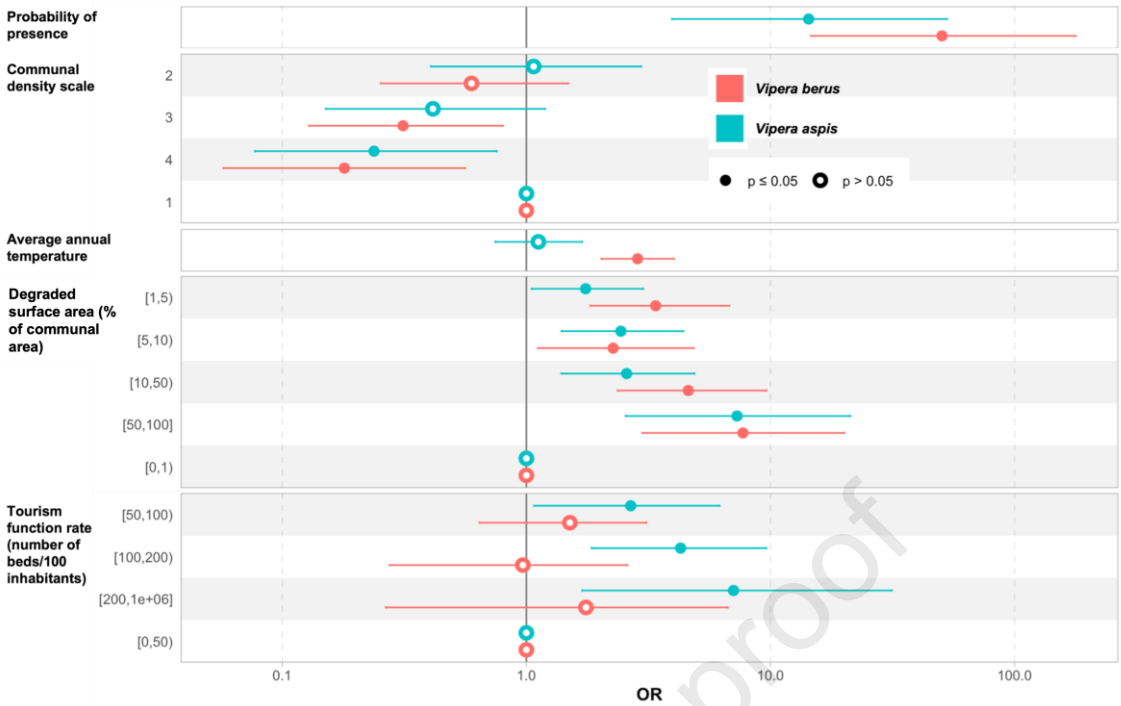

Figure 3. Comparison of the odd ratios (OR) of the variables used in model 0 according to the most likely species in each commune.

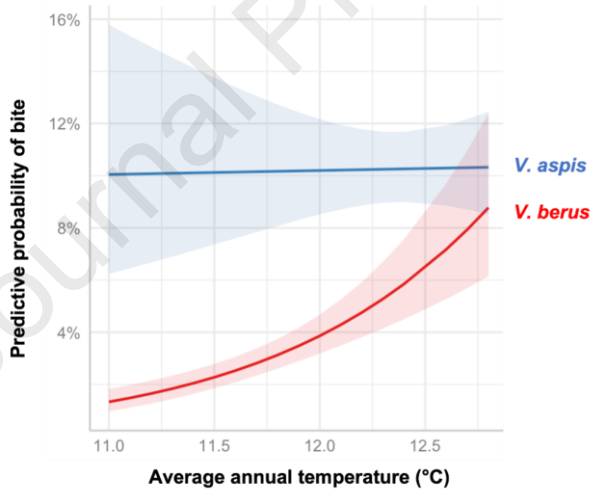

Figure 4. Effect of the interaction between mean annual temperature and viper species on bite probability.

3.4. Determinant of bite numbers

Model 4 (Zero-Inflated Negative Binomial) indicates that none of the independent variables tested appear to affect the number of structural zeros, i.e. whether or not zero bite observations are part of the counting pattern. In contrast, according to Model 5 (Hurdle Negative Binomial), in the presence of *V. aspis*, when the probability of viper presence is high and when the mean annual temperature increases, it becomes more likely that at least one bite is observed (see Supplementary Material 2). In both models, the risk of a higher number of bites increases significantly with an increase in the degraded surface area (from more than 10% in model 5, and

even 1% in model 4), and decreases when the communal density decreases (low-density and very low-density communes). In model 4, the increase in the probability of the presence of vipers as well as the increase in the tourist function rate above 100 beds/100 inhabitants positively influences the number of bites.

4. Discussion

Snake bites resulting from human-animal encounters vary both seasonally and geographically. To our knowledge, this study is the only one to develop a spatially informed approach to the risk of viper bites, in four regions where the risk seems to be the highest in France (Jollivet et al., 2015). As expected, viper's probability of presence extracted form correlative modelling at the municipality level positively influenced the risk of being bitten (multiplied by 3 for a variation in probability of 0.25 from 0.5). This variable also explained the variation in the number of bites as shown by the counting statistic models. Bites were more frequent in Pays de la Loire than in Centre region and more frequent in Bretagne than in Normandie.

The period of highest activity for vipers in the summer, especially for males and breeding females. Accordingly, the peak of bites occurs in June and July. Winter bites are exceptional and are most likely the result of animals being disturbed in their winter retreat. Regarding climatic conditions, it has already been shown that temperature and solar radiation parameters have a strong influence on the probability of presence of vipers in the region, with a strong contrast between the two species. The adder is able to withstand relatively cold weather conditions when compared to the asp viper (Lourdais et al., 2013). Our logistic regressions show that the mean annual temperature played a significant role in the bite risk (a variation of +1°C multiplies the risk by 1.83 to 1.92 depending on the model). There was a significant interaction between species and mean annual temperature. Interpreting the interaction with reference to how temperature affected the species variable, the risk of biting by *V. aspis* appeared to be constant while it gradually increased for *V. berus*. This result must be tempered with our own observations of bites, which occurred at rather milder temperatures, and on average lower in municipalities where *V. berus* is predominant. This result likely reflects contrasted thermal ecology between the two species (Lourdais et al., 2013).

Habitat is an important variable in explaining the distribution of the asp viper and adder (Gentilli et al., 2011; Guillon, 2012). We therefore expect the risk of bites to follow the same trends. The hedgerow landscape is an important part of the living environments of both species, as they are rich in hedgerows. Snakes appreciate hedgerows for their richness in prey and for their numerous refuges, as well as for the herbaceous margin at the foot of the hedge used for basking activities (Lourdais et al., 2015). In France, a land-use study of *V. aspis* observation stations carried out in Burgundy showed that dry grasslands, but also semi-open environments

(corresponding in particular to fallow lands or other bushy areas) have the highest levels, clearly above those of the study sample or their regional share (Varanguin and Sirugue, 2012). Thus, municipalities where associations of hedgerows or edges, but also perennial crops (only in univariate analysis) exceed 5% of the territory have an increased risk of being bitten, as compared to municipalities where the territory is composed of meadows or arable land, which are open environments. In general, *V. berus* prefers herbaceous and more humid microhabitats (Guillon et al., 2014). It is often found in peat bogs, rocky pastures and wet meadows (Dewynter, 2011).

In support with our hypothesis, we have also shown that soil transformation had a positive effect on the risk of bites. In the same way, the more the land is artificially modified, the more the number of bites increases. Using a land-use approach, we observed the same trend: denser urban cover increased the risk of bites. Similarly, the lower the municipal density, the lower the bite risk. It has already been shown in northern Italy (Lombardy) that urban areas have a highly positive effect on the presence of the asp viper (compared to the adder). One hypothesis put forward by the authors of this study is that urban areas constitute thermophilic habitats that could be selected by the asp viper (Gentilli et al., 2011). Heat-storing solid and rocky substrates (including asphalt) are good places for thermoregulation (Varanguin and Sirugue, 2012). The presence of traffic routes (streets, car parks, in industrial and commercial areas) and waste dumps or areas under construction (only in the univariate approach) are thus factors that increased the risk of a bite occurring in our series. The 7 cases of bites on the public highway illustrate this. However, dense cities do not represent a habitat of choice for these animals and the positive effect would only be due to similar "ecological preferences" on the part of vipers and humans (Gentilli et al., 2011). We found that more than half of the bites occurred in the individual homes (terrace, lawn) during a garden-related activity (weeding, mowing, playing in the lawn, etc.), which would indicate municipalities with many greenery areas, both individual (private gardens, vegetable gardens) and public.

The convergence of habitats selection should favour human/wildlife encounters (König et al., 2020; Soulsbury and White, 2015). The coastal towns of the Pays de la Loire and Brittany and the preserved agricultural landscapes (Vendée bocage in the Pays de la Loire) are areas of tourist attraction. The municipalities with a high tourist function are concentrated on the coast and in the mid-mountain areas. Only 6% of the national population resides year-round in the 6,000 French municipalities with a tourist function rate of over 100 beds per 100 inhabitants, even though these municipalities account for 60% of the supply of tourist beds (Gauche, 03/2017). The increase in the tourism function rate above 50 beds/100 inhabitants is strongly associated with an increase in the risk of occurrence and frequency of bites, whatever the statistical approach considered (univariate, binomial or counting). Similarly, but only in the univariate approach, the bites tended to take place in the communes with the highest proportion of second homes. Some tourist activities, which are practiced in the summer, do favour encounters with snakes. Nearly

half of the bites were observed during an activity related to nature (hiking, camping) in the period under consideration. When comparing the role of tourism pressure on the risk of bites for each of the two species, it was only significant for *V. aspis*. Importantly, the reasoning we have adopted also make the approximation that any encounter between man and animal results in a bite, which is not necessarily the case. It depends on the behavioural traits of the species or the circumstances of the human/animal encounter (Martín et al., 2022). Simple measure can be applied to minimize bite risk from vipers since these shy animals will first respond to disturbance by feeling or using display behavior. Bite is only the last defensive option, and notably when escape is not possible. Overall, the viper bites recorded in our study are concentrated on the south coastline of Pays de la Loire region, where *V. aspis* is the most likely species but also the area that is subject to the greatest tourist pressure in our area of interest (in terms of the rate of tourist activity).

This study was carried out on data collected over a period of more than 10 years. This is a relatively long period of time on the scale of the territory, during which the landscape of western France may have undergone profound local changes, particularly in response to changes in demography, agricultural practices and tourist demand (Godron and Forman, 1983). The same applies to viper populations with both species showing important declines in the area in relation with habitat degradation (Guiller et al., 2022).The adder seems to be much more sensitive than the asp viper to landscape transformations, such as cultivation, pine forestation or the drying up of wetlands (Dewynter, 2011). Even though the asp viper is influenced by human activities that reduce its colonization in some areas, it currently has a higher recolonization dynamic with a greater degree of dispersion than the adder (Ursenbacher, 2005). The impact of climatic changes and extreme weather events on the future distribution of the two species require specific attention.

Finally, precise knowledge of the municipalities where the risk of being bitten could be the highest is of great interest because it allows public decision-makers to put in place measures to prevent the public from being bitten and to protect areas where vipers are present. It can also be a tool to better distribute antivenoms, expensive products for which shortages are possible (Boels et al., 2020). However, care should be taken as this is a double-edged sword that could lead to the desertion of tourists or worse to the destruction of vipers or their habitats.

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Key Messages:

- Even at a fine scale, the distribution of viper bites is inomogeneous.
- The probability of viper presence and human population density are elements of the bite risk
- Tourist pressure and the scarcity of viper habitats condition the risk of bites.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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