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Distribution and indicator value of intertidal centipedes from Mediterranean beaches within and around Port-Cros National Park (Southern France), with proposal of a simplified monitoring (Chilopoda)

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Abstract. – A study on centipedes living on beaches within and around Port-Cros National Park was conducted during the spring of 2019, using hand-collection along transects. One hundred and twenty chilopods (108 of them being Geophilomorpha) were collected, including the halophilous species *Henia bicarinata* (Dignathodontidae), *Geophilus fucorum* and *Tuoba poseidonis* (Geophilidae). The halophilic character of *H. bicarinata* and *G. fucorum* was confirmed on the seashore of continental France while *T. poseidonis* was considered strictly halophilic. *Pachymerium ferrugineum* (Geophilidae) was considered only halotolerant, in the way it is not restricted to the coastline area. The dominant sediments were observed to have a moderate influence on the presence of halophilous and halobiontic geophilomorphs, with gravel sediments having a more favourable effect. In addition, microhabitats provided by pebbles are of significant importance for halophilic species while the presence of stranded *Posidonia* seems useful for these species. The availability of driftwood is favourable only when it gives a limited contact with the substrate or the stranded *Posidonia* layer. Lastly, the impact of human frequentation was very significant regarding halophilic species; all these species were found to be absent where human activity was high. The presence or absence of halophilic centipedes well shows the conservation state of the shore for species living in this habitat. An experimental easy monitoring with identification sheets is given to determine the conservation state of beaches in South-Eastern France.

Résumé. – **Répartition et valeur indicatrice des Chilopodes intertidaux des plages méditerranéennes dans et autour du Parc national de Port-Cros (sud de la France), avec proposition d'une méthode d'évaluation simplifiée (Chilopoda)**. Une étude sur les Chilopodes des plages dans et autour du Parc national de Port-Cros a été réalisée au printemps 2019, à l'aide de récoltes manuelles dans des transects. Cent-vingt chilopodes (108 de ceux-ci étant des Geophilomorpha) ont été collectés, incluant les espèces halophiles *Henia bicarinata* (Dignathodontidae), *Geophilus fucorum* et *Tuoba poseidonis* (Geophilidae). Le caractère halophile d'*H. bicarinata* et de *G. fucorum* est confirmé sur le littoral français, tandis que *T. poseidonis* est considéré comme strictement halophile (= halobie). *Pachymerium ferrugineum* (Geophilidae) est seulement considéré comme halotolérant, dans le sens où il n'est pas restreint aux milieux salés littoraux en France. Les sédiments dominants ont une influence modérée sur la présence des halophiles et halobiontes, avec les sédiments graveleux ayant un effet plus favorable. En complément, les micro-habitats fournis par les galets sont d'importance significative pour eux ; quant aux posidonies échouées, elles semblent utiles. La disponibilité de bois échoués est considérée comme favorable uniquement quand ils sont en contact étroit avec le substrat ou la couche de posidonies échouées. Enfin, l'impact de la fréquentation humaine est très significatif sur les espèces halophiles : toutes ces espèces sont absentes quand la fréquentation humaine est élevée. La présence ou absence des chilopodes halophiles est un bon indicateur de l'état de conservation des plages pour les espèces d'Arthropodes inféodées à cet habitat. Un suivi expérimental simplifié avec des fiches d'identification est donné pour déterminer l'état de conservation des plages dans le sud-est de la France.

Keywords. – Monitoring, halophilic species, Hyères Var, wrack, Geophilomorpha.

Centipedes are predators, mainly feeding upon other invertebrates living in or on the soil, or under its natural shelters (Demange, 1981; Iorio, 2014). There are 148 species and 4 subspecies

of centipedes currently reported in metropolitan France, with more than 42% of endemics/sub-endemics (Iorio, 2019a; Iorio & Geoffroy, 2019). This group also contains many stenotopic species, and 19 species are considered "sensitive species" (Iorio, 2014; Iorio *et al*., 2015). All these characteristics indicate the high conservation value and the potential biological indicator ability of centipedes. Despite these facts, Chilopoda are very much neglected in official arthropod protection practices and in environmental impact studies.

Among specialized species of centipedes, ten are considered halophilic. Three exist along the Mediterranean coast only: *Henia bicarinata* (Meinert, 1870) (Dignathodontidae), *Geophilus fucorum* Brölemann, 1909, and *Tuoba poseidonis* (Verhoeff, 1901) (Geophilidae) (Iorio, 2014). Silvestri (1903) was the first to introduce the term of "halofili genuini" to qualify the geophilomorphs only living on the seashore. Some of the better known halophilous species of the Atlantic coast are so closely related to the intertidal environments that they are considered as halobiontic (e.g. Cloudsley-Thompson, 1948; Delamare-Debouttteville, 1948; Barber, 1992, 2006, 2009, 2011; GRETIA, 2010; Iorio, 2014; Racine & Iorio, 2017). But for the French Mediterranean halophiles, which are much less well known, the habitat specialisation has never been confirmed, and they have been classified as halophilous (Caziot, 1925; Brolemann, 1926, 1930; Demange, 1981) with some uncertainty regarding *H. bicarinata* (Iorio, 2014; Iorio & Noël, 2017). The case of *H. bicarinata* remains unclear because of some observations in adjacent Mediterranean countries, in which it is found in different environments (Minelli & Iovane, 1987; Zapparoli *et al*., 2004; Simaiakis *et al*., 2004, 2005; Zapparoli, 2009). However, on the French seashore, these three species have seriously declined in the Alpes-Maritimes and the eastern part of Var department where they have been regularly observed in the first quarter of the 20th century (Iorio *et al*., 2015).

Ponel (1983, 1984) first observed a valid species of centipede, the Geophilidae *Pachymerium ferrugineum* (C. L. Koch, 1835), in Port-Cros National Park. This widely distributed geophilid, although historically considered typical of the seashore (e.g. Brolemann, 1926, 1930; Palmén & Rantala, 1954), cannot be defined as strickly halophilous because it was repeatedly sighted in other, non-intertidal, habitats (whether in France or elsewhere, e.g. Minelli & Iovane, 1987; Andersson *et al*., 2005; Zapparoli, 2006; Iorio, 2014). Later, a myriapodological paper by two researchers specialising in Diplopoda added ten species of centipedes from the Hyères islands (Port-Cros and Porquerolles), including the observation of one specimen of *Henia bicarinata* (Dignathodontidae) on Porquerolles (Mauriès & Nguyen Duy-Jacquemin, 2001). Finally, a recent paper with new data provided a provisional total of 15 species for these islands (Iorio & Noël, 2017), with the discovery of *Geophilus fucorum* and *Tuoba poseidonis* in Port-Cros.

Because of their high conservation value and because of the strong human impact that Mediterrean beaches experience, we wanted to assess the distribution of intertidal centipedes within and around the National Park of Port-Cros (Southern France), with three main objectives: (i) verifying the typology of habitat specialisation for these species, (ii) assessing the impact of habitat characteristics including human frequentation and (iii) proposing a simplified protocol for monitoring centipedes of these habitats.

Material and methods

Sampling. – To enable more detailed analyses and comparisons than with traditional visual surveys, the visual research was generally carried out by two operators: the first author and a trained operator, in 19 predefined transects (table I).

The envisaged transect length was 100 metres. The surface of the studied beaches is heterogeneous, which renders it impossible to always use the same lengths for the transects

and so we adapted the length from 15 to 100 metres (table I); and we almost always had the same width from the seawater line (10 metres, with only one exception: the transect TR13 = only 4 metres up to the rocky cliff). The start and end points of each transect have been geo-localized and the dimensions measured with the help of a GPS. When cumulating both operators' duration of field research, it has not exceeded 3 hours for the transects ≤ 50 m in length; 5 hours

Table I. – General information on the 19 transects studied and their characteristics (all in Hyères municipality). EI = Étienne Iorio; DG = David Geoffroy; MC = Martine Couturier; GU = Gaëlle Urvoy. Presence of pebbles (as shelters: pebbles ≥100 mm only): 1 = poorly present or no pebble; 2 = numerous; 3 = pebbles are the dominant sediments. Stranded *Posidonia*: 1 = poorly present or none; 2 = moderately present; 3 = highly present. Driftwood: 0 = none; 1 = poorly or moderately present; 2 = numerous. Human use: 0 = none; 1 = poorly to moderately used; 2 = highly to very highly used.

N° of transect	Date	Locality	Length (m)	Operator	Dominant sediments	Presence of pebbles	Quantity of stranded *Posidonia*	Quantity of driftwood	Human use
TR1	1.IV.2019	Near the Étang de l'Anglais	100	EI-DG	**Sand**	**2**	**3**	**0**	**1**
TR2	1.IV.2019	At the west of the Étang de l'Anglais	100	EI-DG	**Sand**	**1**	**3**	**1**	**2**
TR3	1.IV.2019	At the east of the Plage du Pentagone	100	EI-DG	**Sand**	**1**	**2**	**0**	**2**
TR4	1.IV.2019	Plage du Pentagone	100	EI-DG	**Sand**	**1**	**1**	**0**	**2**
TR5	1.IV.2019	Plage du Pentagone (west side)	100	EI-DG	**Sand**	**1**	**1**	**0**	**2**
TR6	2.IV.2019	Plage d'Argent (west side)	100	EI-DG	**Sand**	**1**	**3**	**1**	**2**
TR7	2.IV.2019	Small cove below the Fort du Langoustier	30	EI-DG	**Pebbles**	**3**	**2**	**0**	**0**
TR8	2.IV.2019	Plage du Langoustier	100	EI-DG	**Sand**	**2**	**3**	**0**	**2**
TR9	3.IV.2019	At the north of Pointe Maoufat	30	EI-MC	**Pebbles**	**3**	**2**	**0**	**0**
TR10	3.IV.2019	Plage de la Croustillante	100	EI-MC	**Pebbles**	**3**	**2**	**2**	**1**
TR11	3.IV.2019	Plage de Notre-Dame	100	EI-MC	**Sand**	**1**	**1**	**1**	**2**
TR12	4.IV.2019	Plage de Port-Man, west side	30	EI-GU	**Sand**	**1**	**3**	**2**	**1**
TR13	4.IV.2019	Baie de Port-Man, east side	15	EI-GU	**Gravels**	**2**	**2**	**0**	**0**
TR14	4.IV.2019	Calanque Longue	15	EI-GU	**Sand**	**2**	**3**	**1**	**1**
TR15	4.IV.2019	Plage de la Palud	100	EI-GU	**Sand**	**1**	**1**	**2**	**2**
TR16	5.IV.2019	Plage du Sud	50	EI-GU	**Sand**	**2**	**3**	**2**	**2**
TR17	5.IV.2019	Anse de Fausse-Monnaie	20	EI	**Sand**	**1**	**3**	**1**	**1**
TR18	5.IV.2019	Fond de la Rade	40	EI	**Gravels**	**2**	**1**	**1**	**0**
TR19	5.IV.2019	Beach at the west of Calanque du Four à Chaux	100	EI	**Pebbles**	**3**	**1**	**0**	**2**

for those > 50 m in length. The smallest transects (≤ 20 m) were limited to 1.5 hour of prospecting. The aim was to better balance the pressure of prospecting.

As has done successfully many times in the field, the specimens were manually collected during spring after an exhaustive daytime visual search under all likely shelters for the majority of centipedes (e.g. Iorio *et al*., 2015): pebbles, rocks, logs, dehiscent bark on dead trees, stranded *Posidonia oceanica*, litter and soil substrate up to 15 cm in depth. When thick *Posidonia* "banquettes" were present, these were examined in depth in many places. We note that pitfall traps (= Barber traps), frequently used to study soil arthropods such as ground spiders and carabids, are not effective for the collection of centipedes, as a many of these do not fall into these traps, particularly the Geophilomorpha (Gerlach *et al*., 2009; Voigtländer & Decker, 2014; Iorio & Racine, 2018). Also, De Matthaeis *et al.* (2019) have observed that manual collection in litter and in natural shelters is preferable to pitfall traps when collecting seashore geophilomorphs.

In each transect (fig. 1), we made an additional division into two subtransects when we collected specimens (0-4 m from the seawater line, and >4 to 10 m of the same; TR13 corresponding only to the first) to be more precise regarding the location of the species and to study the habitat specialisation. The following morphotypes were separated in the field: *Scutigera coleoptrata, Lithobius sp., Cryptops sp., Pachymerium ferrugineum, Henia bicarinata* and a morphotype containing *Tuoba poseidonis* and *Geophilus fucorum*. After this separation, which has been useful later to determine the spatial distribution of species in the subtransects, the specimens were immediately placed in 70° ethanol and labelled with all relevant information.

Habitat characteristics. – The transects represent the different types of beaches according to several variables that illustrate the potential influences: dominant sediments, presence of pebbles as natural shelters if dominant sediments are finer (sand or gravel), presence or absence of stranded *Posidonia* and practical estimation of its thickness when present, presence or absence

Fig. 1. – Example of the transect TR12: 30×10 m with subtransects 0-4 m and >4-10 m.

of driftwood, human frequentation. Some of these parameters have sometimes been quoted as beneficial for halophilous centipedes (e.g. stranded *Posidonia*), but with scattered observations instead of more standardized observations in a more confined area (Brolemann, 1930; Zapparoli *et al*., 2004; Barber, 2009, 2011; Iorio, 2014). Parameters like dominant sediments, driftwood and the influence of human frequentation without direct urbanization or management, as per example intensive footfall, have never been studied for these arthropods. Details on the estimation of variables are given in table II.

Granulometry was evaluated on a visual basis by identifying only the predominant sediments on the surface and on the first fifteen centimetres of the soil (sediments >50% in each transect). We have taken the basis of Auffret & Le Gall (1972) for the class of size of the three main types of sediments, easy to note on the field without the use of a sieve: pebbles (>20 mm); gravels (<20 mm and >2mm); sand (<2 mm). For the pebbles as shelters, the estimation was visual for the presence of large pebbles (≥100 mm). For the driftwood, the size is determined as: <200 mm diameter = small size; ≥200 mm diameter = large size.

The human frequentation has been determined after the numerous observations of the Port-Cros National Park Officers (D. Geoffroy, G. Urvoy and M. Courturier, unpublished data) during all the year. The following distinctions have been noted: 0 = no one goes on the concerned beaches in all the seasons, or only some persons per year; 1 = the concerned beaches are very few visited by tourists during the essential of autumn, of winter and beginning of spring (1 to 10 persons per week), and used by 10 to 30 persons per day from June to the middle of September; 2 = the concerned beaches are used by 1 to 10 persons per day during the winter, by 10 to 50 persons per day during the essential of autumn and the beginning of spring, and by several hundreds of persons per day from June to the middle of September. Thus, these differences are summarized as the following criteria (table II): 0 = none, 1 = poorly to moderately used, 2 = highly to very highly used.

Identification. – Almost all French centipedes require a microscopic examination, using a magnification from 10 to 50 times, or sometimes more, with the references of Brolemann (1930), Iorio (2010) and Iorio & Labroche (2015). *Scutigera coleoptrata* (Linnaeus, 1758), recognizable in the field without any doubt, has not been collected; but it has been noted with the same details as for the other species.

Analyses. – To carry out more relevant comparisons within our section "Ecological parameters" (below), we calculated the number of individuals of each species in each transect on

Table II. – Class details of estimated abiotic factors.

Dominant sediments	Presence of pebbles (1-2 = on thinner dominant sediments)	Stranded *Posidonia*	Driftwood	Human use
Pebbles	1 = pebbles poorly present or no pebble	1 = poorly present (some small piles, or mixed with substrate) or none	0 = none	0 = none
Gravels	2 = numerous pebbles	2 = moderately present (small "banquettes")	1 = driftwood poorly or moderately present (<10 of small size or <5 of big size)	1 = poorly to moderately used
Sand	3 = pebbles are the dominant sediments	3 = highly present (thick "banquettes")	2 = numerous driftwood (>10 of small size or >5 of big size)	2 = highly to very highly used

a unit surface of 1000 m² with the aim to harmonize the data made on transects equal in width (with one exception), but different in length. To enable better comparisons and statistical tests than those undertaken only with the use of the species, the gathering into two groups of species is used: halophiles and other centipedes.

Some of the results were analyzed with Chi² statistical tests, using the BiostaTGV website (https://biostatgv.sentiweb.fr/?module=tests). Mapping of all transects are synthetized in the Appendix (fig. S1-S2, table I).

Results

Species diversity. – A total of 120 individuals belonging to 7 identified species and 1 only to genus were identified:

– *Henia bicarinata* (Meinert, 1870) (Geophilomorpha, Dignathodontidae) (fig. 4-5);
– *Geophilus fucorum* Brölemann, 1909 (Geophilomorpha, Geophilidae);
– *Pachymerium ferrugineum* (C. L. Koch, 1835) (fig. 2-3);
– *Tuoba poseidonis* (Verhoeff, 1901) (fig. 6-7);
– *Lithobius calcaratus* C. L. Koch, 1844 (Lithobiomorpha, Lithobiidae);
– *Lithobius* sp.;
– *Cryptops parisi* Brolemann, 1920 (Scolopendromorpha, Cryptopidae);
– *Scutigera coleoptrata* (L., 1758) (Scutigeromorpha, Scutigeridae).

The species linked to French Mediterranean beaches from previous studies (Iorio, 2014), *H. bicarinata*, *T. poseidonis* and *G. fucorum*, have been found in several transects (table III).

Also, *P. ferrugineum* has been collected in 10 transects. Details on all the collected centipedes are given in table III.

Spatial distribution in transects. – Of the 120 centipedes collected, 99 were located between 0 and 4 metres from the seawater line, thus in a part of the tidal zone where the waves are low in intensity, as well as the beginning of the part affected by waves of higher intensity as well as salt spray. The 73 specimens of *Henia bicarinata*, *Geophilus fucorum* and *Tuoba poseidonis* were only observed in this zone.

Pachymerium ferrugineum is the only species that has been found several times in both subtransects: 74.3% of its individuals were collected between 0 and 4 metres and 25.7% between >4 and 10 metres. All other species were only in subtransects from >4 to 10 metres. Our observations are synthetized on fig. 8.

Thanks to the separation into morphotypes, we have been able to make better observations regarding spatial distribution of corresponding specimens. Thus, we can add that: *H. bicarinata* and *G. fucorum* were between 1 and 4 meters from the seawater line; *T. poseidonis* was always present between 0.7 and 3 meters of the same; *P. ferrugineum* extends up to 10 meters from the seawater line.

Ecological parameters. – All dominant sediments contain halophilic centipedes, but gravels and pebbles are those with the higher percentages, especially gravel sediments. Taking into account all centipedes and for the unit surface of 1000 m² per transect, we calculate 158, 173 and 78 specimens in beaches dominated by pebbles, by gravel and by sand sediments respectively and for all the individuals of the three halophiles only, 94, 163 and 18 specimens. At the species level, we can observe that the numbers of *H. bicarinata* are higher in gravel beaches (85.9% of the whole), there are few *G. fucorum* in pebble beaches with higher numbers in sandy beaches, although overall numbers are low and that *T. poseidonis* has higher numbers in pebble beaches (55.3%), also high in gravel beaches (43.3%) but very few specimens in sandy beaches.

Halophilic species were mainly associated with gravel sediments, while their relative abundance slightly decreased with pebbles and strongly with a sandy substrate (fig. 9). Relative abundance of halophilic species decreased with increasing cover of both seagrass and driftwood (fig. 10). We also underline the fact that the same species are absent when there are

Fig. 2-7. – Some of the centipede species of the shore, living specimens. – **2-3**, Two specimens of *Pachymerium ferrugineum* (C. L. Koch). – **4-5**, Two specimens of *Henia bicarinata* (Meinert). – **6-7**, Four specimens of *Tuoba poseidonis* (Verhoeff). *(Photographs: É. Iorio).*

Table III. – Species and number of individuals per transect. Species codes: Geoph = Geophilomorpha, Litho = Lithobiomorpha, Scolo = Scolopendromorpha, Scuti = Scutigeromorpha; *G. fuco* = *Geophilus fucorum*, *H. bica* = *Henia bicarinata*, *P. ferru* = *Pachymerium ferrugineum*, *T. pose* = *Tuoba poseidonis*, *L. calc* = *Lithobius calcaratus*, *C. pari* = *Cryptops parisi*, *S. cole* = *Scutigera coleoptrata* (halophilic species are underlined).

Order/ species	TR1	TR2	TR3	TR4	TR5	TR6	TR7	TR8	TR9	TR 10	TR 11	TR 12	TR 13	TR 14	TR 15	TR 16	TR 17	TR 18	TR 19	Tot
Geoph	**7**	**0**	**0**	**0**	**0**	**0**	**23**	**0**	**18**	**10**	**0**	**7**	**6**	**2**	**2**	**4**	**2**	**27**	**0**	**108**
G. fuco	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0	0	1	1	0	4
H. bica	4	0	0	0	0	0	0	0	2	5	0	0	5	0	0	0	0	5	0	21
P. ferru	1	0	0	0	0	0	5	0	10	3	0	5	0	2	2	4	1	2	0	35
T. pose	2	0	0	0	0	0	18	0	6	2	0	0	1	0	0	0	0	19	0	48
Litho	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**1**	**0**	**1**	**0**	**0**	**0**	**2**	**1**	**2**	**0**	**8**
L. calc	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	2	0	5
L. sp	0	0	0	0	0	1	0	0	0	1	0	1	0	0	0	0	0	0	0	3
Scolo	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
C. pari	0	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	2
Scuti	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**
S. cole	1	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	2
Total	**8**	**0**	**0**	**0**	**0**	**1**	**24**	**0**	**20**	**11**	**0**	**8**	**6**	**2**	**2**	**6**	**3**	**29**	**0**	**120**

no stranded *Posidonia*. *H. bicarinata* and *T. poseidonis* are lacking when pebble shelters are in too low a number or absent on beaches with other dominant sediments (sand or gravels).

The transects on beaches unused or very rarely used by humans have concentrated 91% of all records of *Geophilus fucorum*, *Tuoba poseidonis* and *Henia bicarinata* individuals, while the transects on poorly to moderately used beaches have 9%. Halophiles are not present on beaches with high to very high human use. The halophiles are by far dominant *vs*. the non-halophiles in the first case but not in the second (fig. 11). This distribution is statistically significant (χ^2 test, χ^2=85.22, P<0.001). We note that the transects in the highly to very highly used sites (level "2") are the most numerous in our study (n = 10), followed by those in the poorly to moderately used ones (level "1") (n = 5) and the unused (level "0") (n = 4).

Discussion

Faunistic and conservation interest

The three species that we primarily focused on, *Henia bicarinata*, *Geophilus fucorum* and *Tuoba poseidonis*, are very rare and with a recognized "patrimonial" interest in Provence-Alpes-Côte d'Azur region (= "déterminantes for the Zones naturelles d'intérêt écologique, faunistique et floristique" (ZNIEFF) of PACA region: Iorio, 2014; CEN PACA, 2017). These species have been found in several sectors of the National Park and its surroundings, including several new venues: in particular, *T. poseidonis* is recorded for the first time in Porquerolles and in Salins d'Hyères (beach near the Étang de l'Anglais). We would like to draw attention to the fact that the beach near the Étang de l'Anglais, which contains *H. bicarinata* and *T. poseidonis*, is outside the National Park and is the only beach of Hyères and more widely of the continental coast of central Var department where these species exist to the best of our knowledge. Some stations on the islands have shown considerable numbers of individuals. These discoveries strengthen the importance of the National Park for them, because at the present time, these are the only recent populations known in South-Eastern France. We recall that the populations of Alpes-Maritimes and of Eastern Var departments have very markedly declined (Iorio *et al*., 2015; É. Iorio, unpublished data).

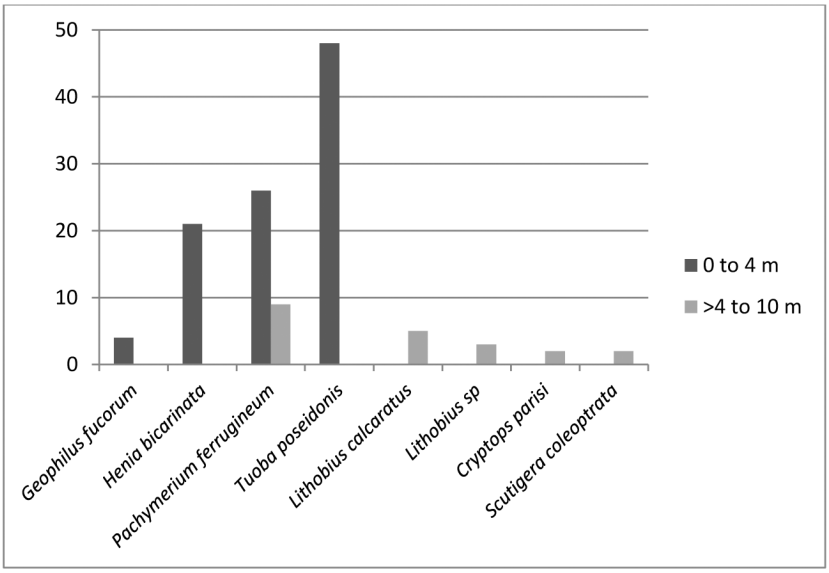

Fig. 8. – Number of individuals per species according to the distance to the sea.

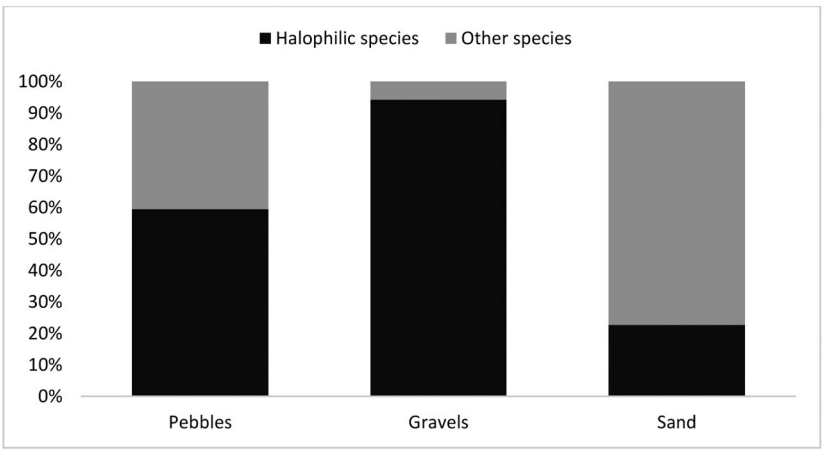

Fig. 9. – Relative abundance of halophilic vs. non-halophilic species of Chilopoda depending on the sediment type.

Spatial distribution on the shore and confirmation of the halophilous character

On the basis of the samples that we collected by separating each transect into two sub-transects as well as our supplementary more detailed observations after morphotype recognition, none of the three species *Geophilus fucorum*, *Henia bicarinata* and *Tuoba poseidonis* have been found at more than approximately four metres from the seawater line. We recall that in the bibliography, *T. poseidonis* was always seen on the seashore and was already considered as strictly halophilic in all of its distribution area (Brolemann, 1930; Minelli & Iovane, 1987; Carpaneto, 2004; Simaiakis *et al*., 2004, 2005; Zapparoli *et al*., 2004, 2014; Barber, 2009, 2011; Deidun *et al*., 2009; Zapparoli, 2009; Iorio, 2014; De Matthaeis & Zapparoli, 2015; Iorio & Noël, 2017; De Matthaeis *et al*., 2019). The sole finding of it in a greenhouse in Helsinki is from 1947 and was resulting from a temporary unacclimatized introduction (Andersson *et al*.,

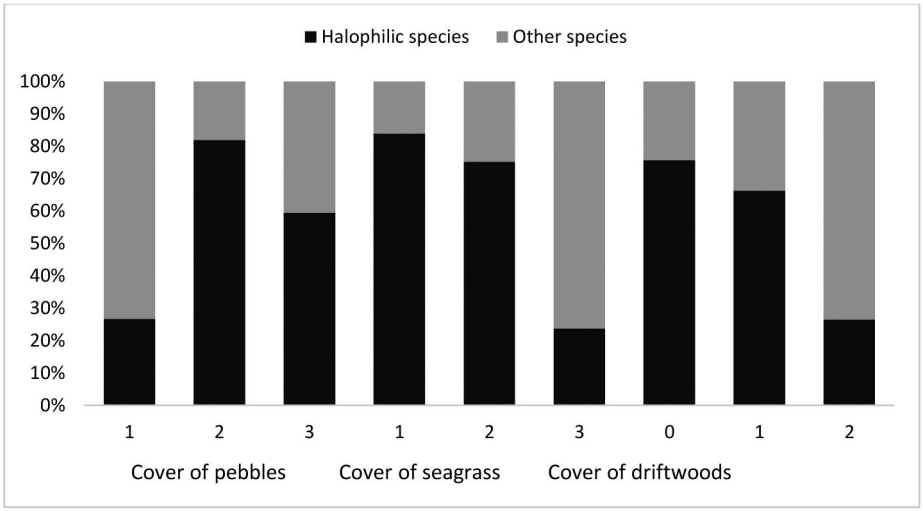

Fig. 10. – Relative abundance of halophilic vs. non-halophilic species of Chilopoda depending on the level of cover of shelter (respectively: pebble: 1 = poorly present or no pebble; 2 = numerous; 3 = pebbles are the dominant sediments; seagrass = stranded *Posidonia*: 1 = poorly present or none; 2 = moderately present; 3 = highly present; and driftwood: 0 = none; 1 = poorly or moderately present; 2 = numerous).

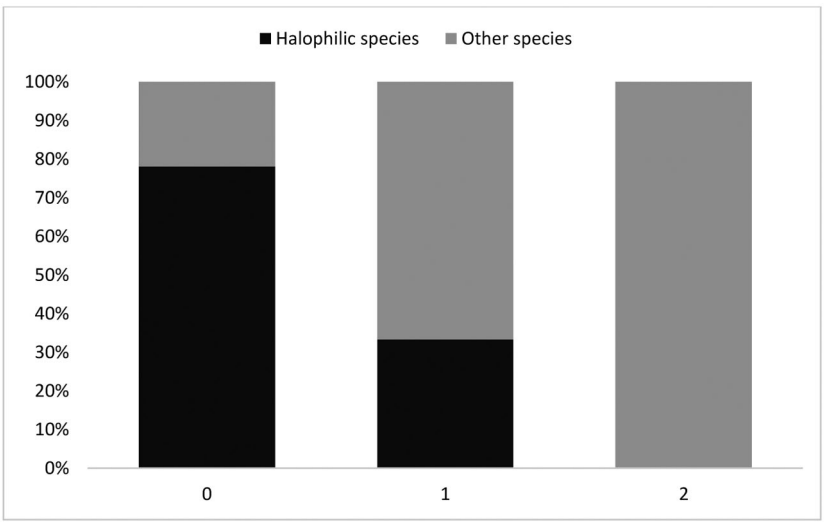

Fig. 11. – Relative abundance of halophilic vs. non-halophilic species of Chilopoda depending on human frequentation (see Material and Methods for class definition); 0 = no human use; 1 = poorly to moderately used; 2 = highly to very highly used.

2005). Also, Garcia Ruiz & Serra (2000)'s record from Toledo Province in Spain must be incorrect, because it notably exceeds the maximum number of pairs of legs for *T. poseidonis*: their very short description must refer to another species of the genus *Tuoba* Chamberlin, 1920, or even to the close genera *Clinopodes* Koch, 1847, or *Stenotaenia* Koch, 1847. It is particularly interesting to note that the location of none of the 48 specimens of *T. poseidonis* exceeded the distance of three metres relative to the seawater line with the closest being only 0.7 metres from it. The spatial occupation of the Mediterranean seashore by *T. poseidonis* is thus very

small, limited to the higher part of the mediolittoral zone of the seashore and to a very narrow part of the lower part of its supralittoral zone. Taking into account all of this information and thanks to the examination of the collection from the Muséum national d'Histoire naturelle (MNHN) during 2018, which allowed one of us to look at many specimens from seashore locations (É. Iorio, unpublished data), we can confirm than *T. poseidonis* can be considered as strictly halobiontic. Also, its spatial distribution on the beaches is very limited and this parameter was previously unknown: that should induce sensitivity in conservation.

For the less well known *Geophilus fucorum*, the same habitat specialisation as for *Tuoba poseidonis* is quoted in the bibliography, but with one formal exception (Minelli, 1982). The case of *G. fucorum* is less well documented even after this study because of the low numbers of individuals found, but the same collection as above led us to see relatively numerous specimens from beaches only; thus, we tentatively consider it as halophilous in our country**.**

For *Henia bicarinata*, as stated in the introduction, at least five formal references quoted it outside the seashore in three countries (Italy, Greece, Malta); the species is more frequently observed from the seashore and is still considered as halophilous by Zapparoli *et al*. (2014). In continental France, despite a lot of data on centipedes of the circum-mediterranean departments of Provence-Alpes-Côte d'Azur region (>2000 records in March 2019) (Iorio, 2019b), *H. bicarinata* has never been found elsewhere than on the seashore; the same can be said for the Pyrénées-Orientales department (Caziot, 1925; Brolemann, 1926, 1930; Demange, 1981; Mauriès & Nguyen Duy-Jacquemin, 2001; Iorio, 2014; Iorio & Noël, 2017). Our present results show that *H. bicarinata* is only present 1 to 4 metres away from the seawater line in beaches of the Hyères territory. The examination of the historic collection of the MNHN strengthens these observations (É. Iorio, unpublished data): in Alpes-Maritimes, between 1897 and 1910, the French myriapodologist Henri-Wilfried Brolemann has found from 2 to 50 specimens of *H. bicarinata* per day of hand collecting on each beach that he has inventoried (several beaches of Juan-les-Pins, of the Cap d'Antibes, of Cannet de Cannes, of Cannes-Croisette, of the Lérins islands; from 1 to 4 days of hand collecting by H.-W. Brolemann on each). Also, Binyon & Lewis (1963) have shown that the French *H. bicarinata* has anatomical and physiological features specific to species restricted to salty habitats; as for *Hydroschendyla submarina* (Grube, 1872) and *Strigamia maritima* (Leach, 1817), two well-known halobiontic geophilomorphs from the Atlantic coast. Finally, Barber (2011) suggests that the cases of species strictly halophilous in some areas and not in others could result from differences or even from isolation between populations (possible ecotypes?). On the French Mediterranean coast, *H. bicarinata* is clearly halophilous.

As for the case of *Pachymerium ferrugineum*, which we have seen occurring two to ten metres away from the seawater line, with more than one quarter of its individuals more than four metres away, the halotolerant character is confirmed. In Germany, Spelda (1999, 2005) and Voigtländer (2004) have shown that it was a species of "extreme" habitats, where the interspecific competition is reduced because of few favourable abiotic factors for centipedes. The higher parts of beaches are xeric and the lowest parts are salty, thus extreme conditions for the majority of centipedes.

The three other identified species, *Cryptops parisi*, *Scutigera coleoptrata* and *Lithobius calcaratus* are considered as accidental species on beaches. We find from our observations that they are 7 to 10 metres away from the seawater line; thus without a link with the salty wet zone. *S. coleoptrata* and *L. calcaratus* are clearly euryecious species, present in a very wide range of habitats, including disturbed and anthropized biotopes; the second is very common in xeric habitats (Iorio, 2014).

Ecological requirements of intertidal centipedes

Sediments and mineral shelters. – Despite more halophiles having been found where gravel is the dominant sediment, we do not think that this abiotic factor has a big influence on their populations. The bibliography quotes almost equally *T. poseidonis* and *H. bicarinata* on sandy beaches as well as gravel, pebble or rocky ones (Carpanetto, 2004; Simaiakis *et al*., 2004, 2005; Zapparoli *et al*., 2004, 2014; Deidun *et al*., 2009; De Matthaeis *et al*., 2019). On the other hand, even when pebbles were dominant, we have noted that the halophile species, particularly *T. poseidonis*, were located in zones where there is a close contact with pebbles and at least a thin layer of finer sediments, including those finer than gravel. Perhaps this factor has a stronger influence at the micro-habitat level? Finally, it is important to specify that in the beaches studied, the ones with sand as the dominant sediment constitute the largest group and are the ones most used by humans: another factor of influence. Pebbles have a very important role as natural shelters for halophiles. It is well known that centipedes are lucifugous and have a high positive thigmotaxis (e.g. Demange, 1981; Iorio, 2014) and particularly favour shelters with a limited contact with substrates such as stones, logs, etc. in the soil. In our observations on Hyères beaches, the beaches with few pebble shelters do not contain *Henia bicarinata* nor *Tuoba poseidonis*, and the same remark applies to beaches without these shelters. On the contrary, the numbers of *H. bicarinata* and especially of *T. poseidonis* are considerable when pebbles are numerous on sandy or gravel beaches, or on pebble beaches in the micro-conditions noted above.

Organic shelters: stranded* Posidonia oceanica *and driftwood. – Numerous authors have quoted *Geophilus fucorum* and *Henia bicarinata*, and especially *Tuoba poseidonis*, as occupying beaches with stranded *Posidonia*; or even that the third species is specific to stranded *Posidonia* (Brolemann, 1930; Minelli & Iovane, 1987; Carpaneto, 2004; Simaiakis *et al*., 2004, 2005; Zapparoli *et al*., 2004, 2014; Barber, 2009, 2011; Deidun *et al*., 2009; Zapparoli, 2009; Iorio, 2014; De Matthaeis & Zapparoli, 2015; Iorio & Noël, 2017; De Matthaeis *et al*., 2019). Our observations tend to confirm that the presence of stranded *Posidonia* is a good factor for halophilous centipedes. The stranded *Posidonia* is a favourable habitat for many invertebrates (e.g. amphipods, isopods, coleopterans, pseudoscorpions, molluscs, etc.) (Deidun *et al*., 2009; Boudouresque *et al*., 2017; De Matthaeis *et al*., 2019) and it appears that its presence benefits the three halophilous predator centipedes. It is worth underlining the fact that the thickness that forms large "banquettes" is not necessary. Halophiles are also present when small "banquettes" or even only some heaps of *Posidonia* exist, or when it is mixed with sediments; the highest numbers being with the lowest presence of *Posidonia* (but not without *Posidonia*).

The presence and quantity of driftwood has no clear influence on the presence or absence of halophiles, because individuals exist when these shelters are scattered or plentiful, but there are more without them. We note that driftwood which had a limited contact with the soil or with the "banquettes" seems much more favourable than others, because in this case, several specimens of *Henia bicarinata* were discovered. *Pachymerium ferrugineum* has also been observed several times. However, the majority of the driftwood did not have this contact, and was not favourable if we take into account the lucifugous character and positive thigmopraxis of centipedes.

Impact of human use of beaches

Based on the statistical analysis above, the level of human use of beaches has clearly not had the same influence on all species if we consider the three halophiles *vs*. the other centipedes.

Halophiles are not present on beaches with high to very high human use. We recall that

the transects in the case of high to very high human use have been those mostly represented in our study (n = 10), followed by those poorly to moderately used (n = 5) and those unused (n = 4). In more detail, the actual sampled surface in the first case has been by far the largest (9500 m², *i.e.* 71.9% of the sampled surface); followed by the second (2650 m², 20.1%) and third (1060 m², 8.0%). Thus, the chances of seeing centipedes were much higher on the most used beaches than on the others, because much more surface had been sampled: it is a positive bias which increases the scope of this research, despite a moderate number of replicates. There is therefore no ambiguity in affirming that human use has a strong impact on the three Mediterranean halophilous geophilomorphs on the seashore of Hyères. Even the halotolerant *Pachymerium ferrugineum* undergoes a decline in its populations if human use increases, but it is much less obvious than with halophiles, particularly *Tuoba poseidonis* and *Henia bicarinata*. Results of this kind are completely new for littoral centipedes, because even if decreasing relative to urbanization or extreme human management of beaches was implied after the global decline observed in South-Eastern France by Iorio *et al*. (2015), it has never been shown that smaller human impacts like footfall, and/or cleaning (Lioult, 2018) or moving of shelters have a clearly negative influence on the most specialized species.

A remarkable aspect is also that where *Tuoba poseidonis* and *Henia bicarinata* are present, many other invertebrates have been seen: numerous amphipods and isopods, coleopterans with many Staphylinidae amongst others, dipterans, molluscs, etc. Conversely, beaches without halophilous centipedes are unfavourable to the invertebrate diversity and density in general: only some scattered amphipods and isopods, some euryecious centipedes such as *Lithobius calcaratus* and some dermapterans such as *Labidura riparia* (Pallas, 1773) (Labiduridae) and the common *Euborellia moesta* (Géné, 1837) (Anisolabididae) are present. For the second author and his colleagues of the National Park, the geophilomorphs, slow moving and fairly large, are easy to search for and to capture on the field. Thus, they could be good "umbrella" species to protect specialized shore fauna.

Conclusion and perspectives

Although total numbers of individuals were quite low, ecological knowledge of littoral species from the area concerned has improved, and a strong halophilous character is clearly confirmed for *H. bicarinata*, *G. fucorum* and especially for *T. poseidonis*. Moreover, their spatial distribution on the beaches was specified for the first time. The other main ecologically beneficial factor is the existence of numerous pebble shelters (in contact with finer sediments at the micro-habitat level), as well as the presence of stranded *Posidonia*.

An important question of this study finds a preliminary answer: the "simple" human use of the beaches, without any urbanization or strong management, has a clear impact on specialized centipedes of the seashore. Relative to its level, the halophiles markedly decline or even disappear if it is too high. This answer helps us to better understand why these species are extinct in all their historic locations in Alpes-Maritimes and in Eastern Var departments. With knowledge of these details and unpublished data found in the collection of the MNHN during 2018 (É. Iorio, unpublished), showing for example that *H. bicarinata* and *G. fucorum* were present on the shore of the Étang de Berre in Saint-Chamas fifty years ago but are seemingly non-existant following recent qualitative research in the same place in 2010 and in 2011, *H. bicarinata*, *G. fucorum* and *T. poseidonis* can be considered as highly threatened in all of the Provence-Alpes-Côte d'Azur region.

The four geophilomorphs most commonly encountered on French Mediterranean beaches are easy to find when present and the three halophiles reflect a beach which overall remains very favourable to life on the shore. It gives us two main perspectives from this work.

Proposal for a conservation measure. – Generally, the presence and the "quality" of favourable natural habitats and micro-habitats for halophiles is especially based on the absence (or almost so) of human use. It thus would be advisable to make enclosures along the shore on a small part of the beaches containing these species, when the seashore is easily accessible to tourists, to avoid all footfall and all displacement of shelters.

The enclosures must include a submerged part of the mediolittoral part (two meters of width) and extend 8 metres above the seawater line. Exceptionally, reducing the latter to 6 metres could be possible.

Proposal for easy monitoring and determining the state of conservation in South-Eastern France. – By extension, the presence or absence of halophiles, particularly of *Henia bicarinata* and of *Tuoba poseidonis*, shows the conservation state of the shore for species living in this habitat.

With this fact, it is possible to propose an experimental "light" monitoring, ideally to be renewed every three years. This monitoring could ensure that currently present halophiles continue to survive, and to detect the colonization of enclosed portions by a new halophiles (e.g. the west side of the beach of Port-Man, close to a station with *Tuoba poseidonis* and *Henia bicarinata* but which has revealed only *Geophilus fucorum* currently). This monitoring shall be based on the identification sheets in Appendix (fig. S3-S6) and preceded by training by an experienced myriapodologist. It involves walking and searching for geophilomorphs in all favourable micro-habitats in the transects (maximum length: 100 m), with identification in two stages.

1) Separation of the main morphotypes with an examination in the field with the help of a hand lens (×10 or ×15 magnification) or a good digital camera; either: *Scutigera coleoptrata,* Lithobiomorpha sp., Scolopendromorpha sp.*, Pachymerium ferrugineum* (large specimens)*, Henia bicarinata* and Geophilidae sp. The Geophilidae sp. will be collected into 70° ethanol. At less than five metres from the seawater line, the Geophilidae sp. will almost always include *Tuoba poseidonis* and/or *Geophilus fucorum*, as well as young *P. ferrugineum*. If there is a doubt regarding any other geophilomorph (possibly including accidental species other than those found before), *a fortiori* at a large distance from the seawater line, the concerned specimen(s) must be put into ethanol. The investigator will stop the process after 1.5 hour of searching for a transect <50 m of length or 3 hours for a transect ≥50 m. The same can be said when the operator has found at least once all morphotypes in a transect, except for *Tuoba poseidonis*/ *Geophilus fucorum* which he must try to collect at least three times.

2) Identification with a low to medium power binocular microscope in the laboratory of the Geophilidae sp. to recognize *Tuoba poseidonis* and/or *Geophilus fucorum*. If there is a doubt regarding a specimen after examination or if it is another species, it will be set aside pending further determination by a specialist. The Lithobiomorpha *sp.* and the Scolopendromorpha *sp.* will be noted but not taken into account because they do not have an affinity for the shore.

After identifications, notation of beaches or transects with a system of points relative to geophilomorph species found. The species are noted as following after their halophilic/halobiontic character and the impact of the human use discussed above: *Pachymerium ferrugineum* = 1 point (only halotolerant; more or less sensitive to the human use, but clearly less than the following halophiles), *Geophilus fucorum* = 2 points (tentatively considered as halophilic), *Henia bicarinata* = 4 points (confirmed as halophilic in France; sensitive to the human use), *Tuoba poseidonis* = 7 points (halobiontic; very sensitive to the human use). The state of conservation of beaches will be established with the total scores obtained from geophilomorphs observed on those beaches: unfavourable: 0; average: 1 to 3; fairly favourable: 4 to 6; favourable: 7 or +. For the current results in our transects, the assessment of the table S1 in Appendix can be applied.

This assessment based on presence/absence is obviously less powerful than an assessment that would focus on populations, but it has the advantage of being much easier and of limiting the amount of sampling.

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Appendix

Table S1. – Assessment of the conservation status of the transects sampled in this study.

Transect	Note	State of conservation
TR1	12	Favourable
TR2	0	Unfavourable
TR3	0	Unfavourable
TR4	0	Unfavourable
TR5	0	Unfavourable
TR6	0	Unfavourable
TR7	8	Favourable
TR8	0	Unfavourable
TR9	12	Favourable
TR10	12	Favourable
TR11	0	Unfavourable
TR12	3	Average
TR13	11	Favourable
TR14	1	Average
TR15	1	Average
TR16	1	Average
TR17	3	Average
TR18	14	Favourable
TR19	0	Unfavourable

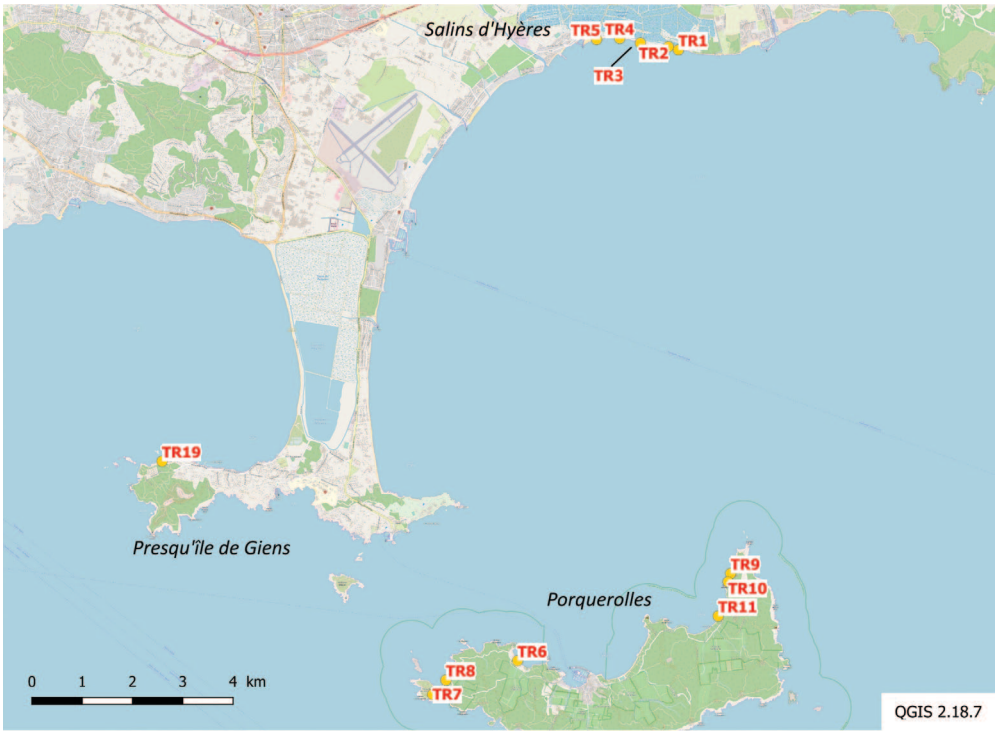

Fig. S1. – Map of transects 1 to 11 and 19. Background of the map: OpenStreetMap.

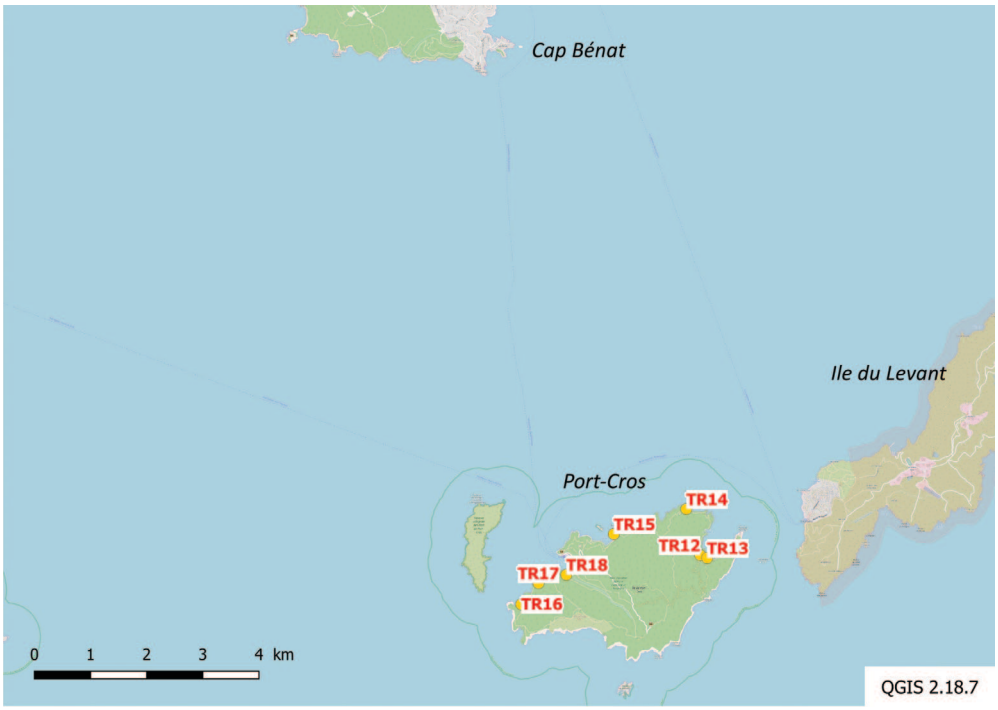

Fig. S2. – Map of transects 12 to 18. Background of the map: OpenStreetMap.

Important remarks for the figures S3-S6 below. – These sheets were designed for the specific purpose, and do not replace an identification key or a long-term training in centipede identification. If a doubt remains, an expert must be asked. They are only useful for adult specimens and for the beaches of the Var department; identification criteria must be assessed with a lens (magnification: 10-15 times) or using high-resolution pictures. Relative scales are ignored in pictures.

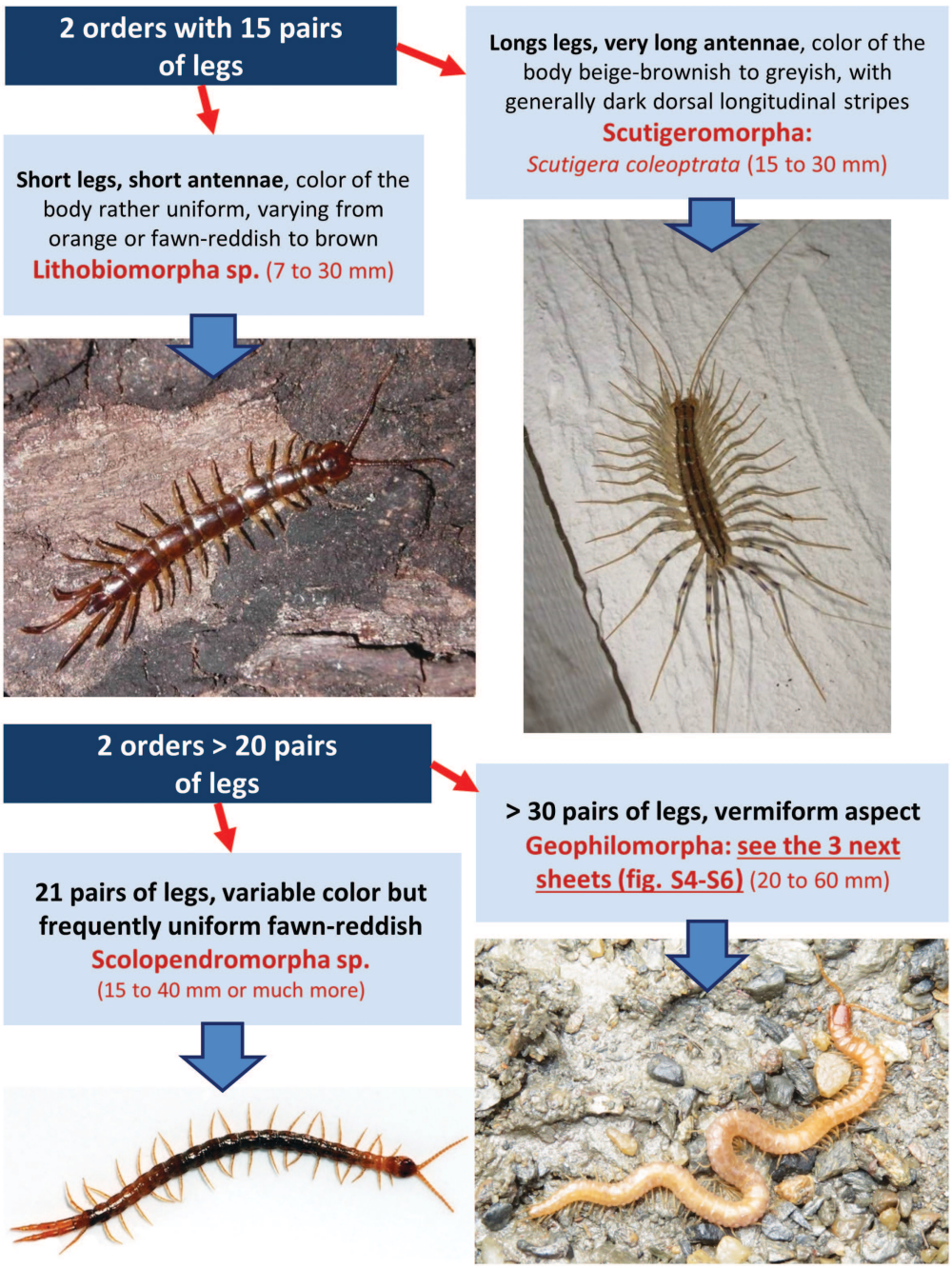

Fig. S3. – Simplified identification sheet of the order of centipedes. *(Photographs: É. Iorio).*

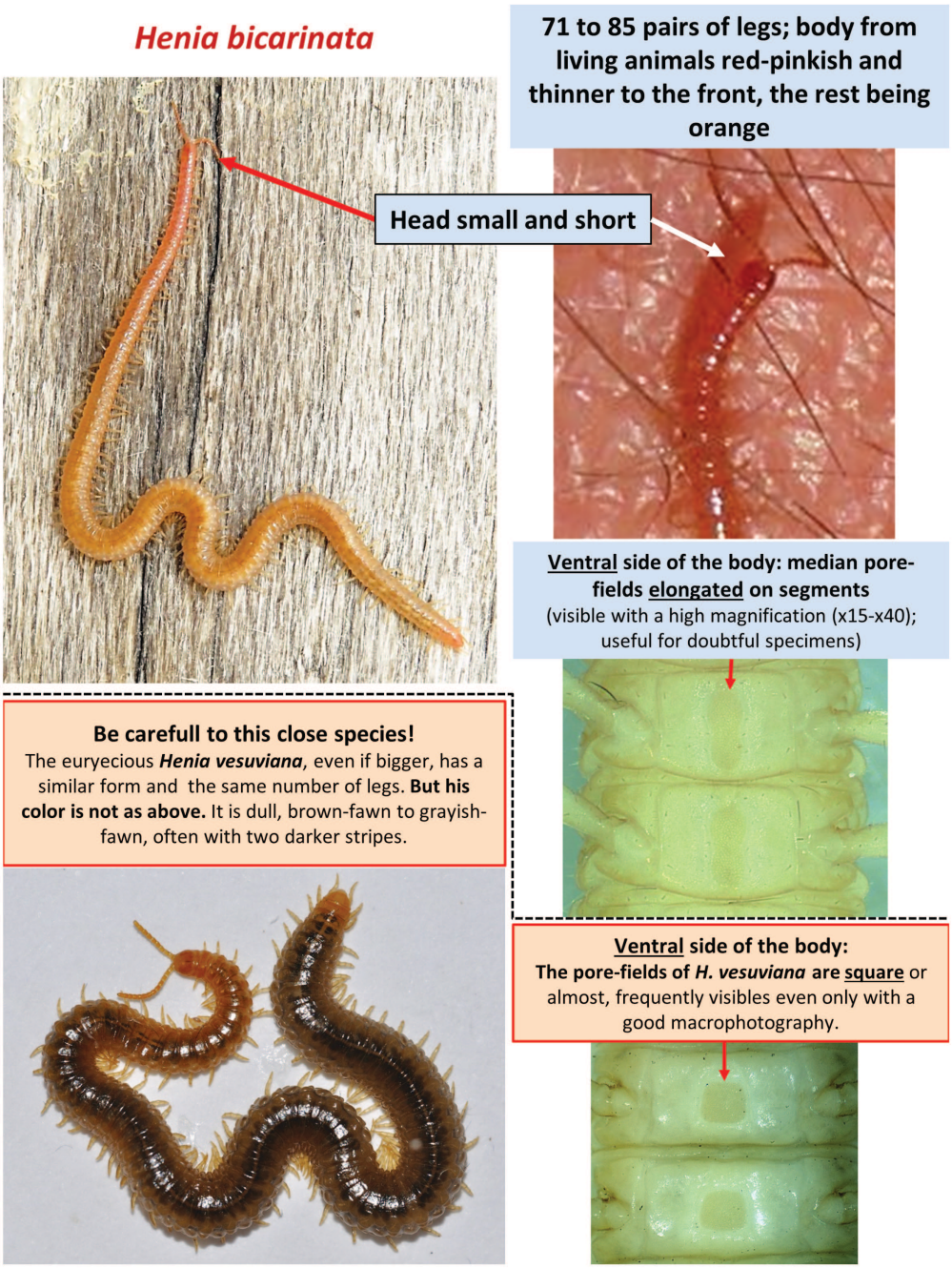

Fig. S4. – Simplified identification sheet of *Henia bicarinata* (Meinert), including difference with the close *H. vesuviana* (Newport). *(Photographs: É. Iorio, except the habitus of H. vesuviana which is from C. Piredda).*

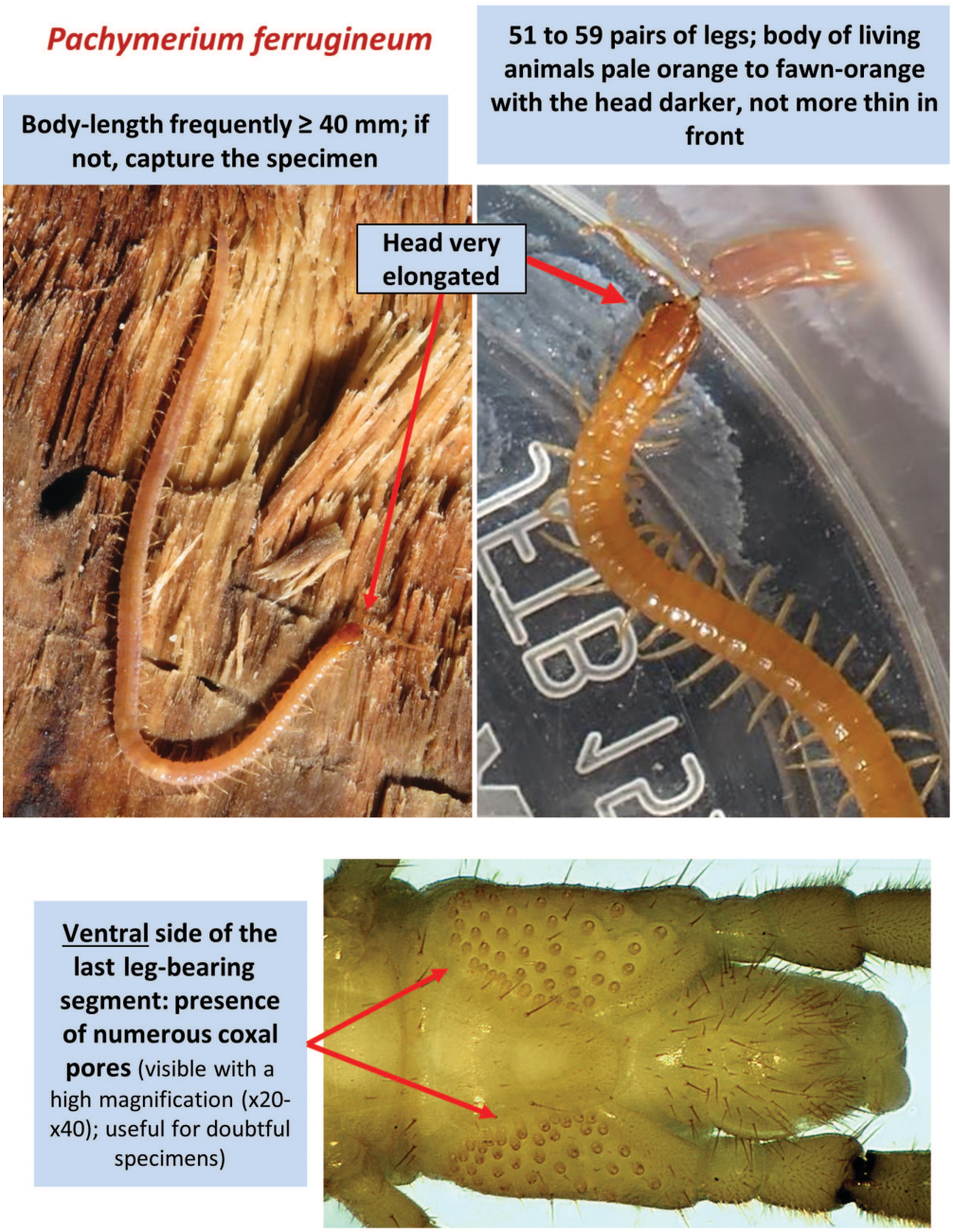

Fig. S5. – Simplified identification sheet of *Pachymerium ferrugineum* (C. L. Koch). *(Photographs: É. Iorio).*

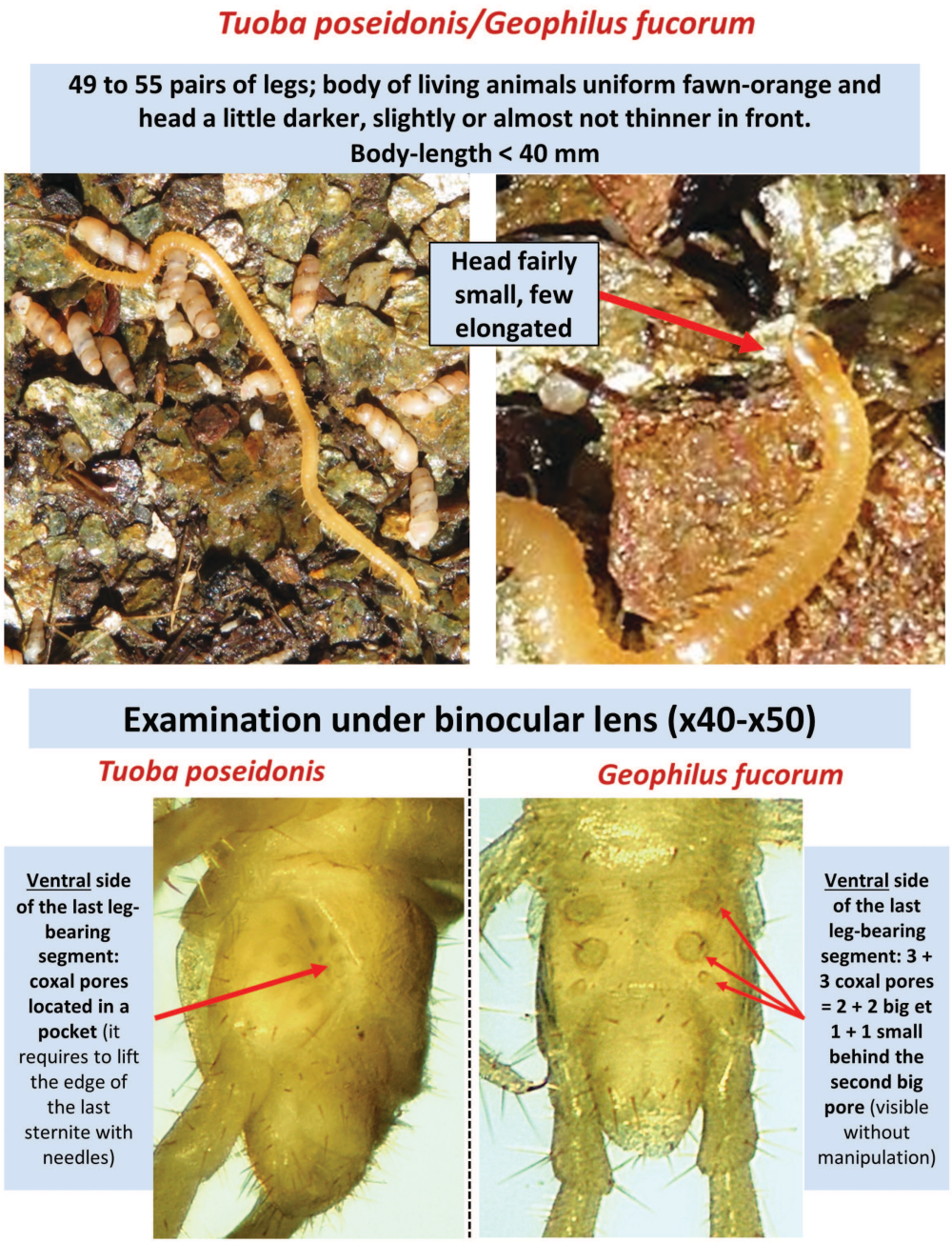

Fig. S6. – Simplified identification sheet of *Tuoba poseidonis* (Verhoeff) and *Geophilus fucorum* Brölemann. *(Photographs: É. Iorio).*