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Female-biased sex ratios unrelated to *Wolbachia* infection in European species of the *Jaera albifrons* complex (marine isopods)

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Abstract

Female-biased sex ratios and reproductive isolation in arthropods can be caused by endosymbiotic *Wolbachia* bacteria that manipulate the reproductive system of their host. *Wolbachia* is particularly common in terrestrial host species, but its frequency in marine arthropods is less well known. Here we asked whether *Wolbachia* bacteria are accountable for the female-biased sex ratio and variation in reproductive isolation levels observed in the four European species of the *Jaera albifrons* complex (marine intertidal isopods). We analysed the sex ratio in young adults reared in the laboratory (indicative of the sex ratio at birth), compared it with the adult sex ratio in natural populations, and performed a molecular survey of *Wolbachia* infection based upon amplification of three gene targets using 11 different protocols tested in 817 individuals from all species of the *Jaera albifrons* complex. One species (*J. ischiosetosa*) had a female-biased sex ratio at birth but showed no sign of infection by *Wolbachia* bacteria. This species, together with two others (*J. albifrons* and *J. forsmani*) also displayed female-biased sex ratio in adults in nature, while the adult sex ratio in the fourth European species (*J. praehirsuta*) was unbiased. A new *Wolbachia* strain was identified in *J. albifrons* and *J. praehirsuta*, albeit at very low frequency in populations. We conclude that *Wolbachia* bacteria are present in at least two species of the *Jaera albifrons* complex, but their prevalence is too low to have any effect on sex ratio and reproductive isolation. A sex ratio distorter other than *Wolbachia* may be acting in some *J. ischiosetosa* populations, and we hypothesize that the adult female excess seen in most species results from habitat-dependent, male-biased mortality in natural conditions.

Keywords: female biased sex ratio, *Wolbachia* endosymbionts, marine crustaceans, *Jaera albifrons*

1. Introduction

Sex allocation theory predicts that frequency-dependent selection favours equal investments into male and female offspring (Fisher, 1999). If production costs are equivalent between offspring of the two sexes then the number of males and the number of females in a population are expected to be balanced. However, there are many constraints to the regulation of this equilibrium (West and Sheldon, 2002), and biased sex ratios are common in nature (Hardy, 2002). Causes of departure from Fisher's null model include in particular local mate competition between individuals for access to sexual partners (e.g. Werren, 1983), meiotic drive on sex chromosomes (reviewed in Jaenike, 2001) and cytoplasmic sex ratio distorters (Cordaux et al., 2011; Taylor, 1990) such as *Wolbachia*.

Wolbachia is a group of cytoplasmic endosymbiotic bacteria found in a large number of invertebrates (Werren et al., 2008). It is predominantly transmitted via female gametes (Werren et al., 2008) and it often promotes its transmission by interfering in the process of reproduction of its host (Rousset et al., 1992; Werren, 1997). *Wolbachia* is notably known to be involved in the conversion of genetic males into functional phenotypic neo-females, a process called feminization (Bouchon et al., 2008; Cordaux and Gilbert, 2017; Rigaud et al., 1999; Werren et al., 2008). It can also induce parthenogenesis in several otherwise sexually reproducing species, or specifically kill the male offspring of infected females (Hurst et al., 1999). Therefore, in absence of compensatory mechanisms (which would be readily favoured by sex ratio selection), *Wolbachia* can cause an increase in the proportion of females in infected populations.

In addition, these bacteria can also play a role in speciation by inducing interspecific cytoplasmic incompatibilities (Rousset et al., 1992; Telschow et al., 2007; Werren, 1997; Werren et al., 2008). For example, studies on wasps of the genus *Nasonia* (Bordenstein et al., 2001; Bordenstein and Werren, 1998; Bordenstein and Werren, 2007) have shown that *Wolbachia* can cause reproductive isolation between two closely related species by bidirectional incompatibility of two strain types. Furthermore, *Wolbachia* can also drive the reinforcement of behavioural isolation between infected and uninfected species (Jaenike et al., 2006).

Although *Wolbachia* is essentially maternally transmitted, its capacity to move into new hosts via horizontal transmission has promoted its spread to different invertebrate clades (Cordaux et al., 2001; Duron and Hurst, 2013; Turelli et al., 2018; Vavre et al., 1999). *Wolbachia* is particularly frequent in arthropods, infecting mites (Breeuwer and Jacobs, 1996), crustaceans (Bouchon et al., 1998) and insects (Werren and Windsor, 2000). Although the prevalence of *Wolbachia* is difficult to quantify, it was estimated to infect 20 to 60% of insects (Sazama et al., 2017; Werren and Windsor, 2000). Few species of marine crustaceans are known to be infected: *Wolbachia* was found in a handful of marine amphipods, isopods, and cirripedes (Bouchon et al., 1998; Cordaux et al., 2012).

In this study, we are interested in the *Jaera albifrons* complex, a group of small (2-5 mm) marine isopods where there are both (i) observations of strongly female-biased sex ratios and (ii) variations in the level of reproductive isolation between species. The *Jaera albifrons* complex includes five intertidal species that live on the shores of the temperate and cold waters of the North-Atlantic Ocean (Bocquet, 1953; Bocquet, 1972; Naylor and Haahtela, 1966). Three of these species (*J. albifrons*, *J. praehirsuta*, and *J. ischiosetosa*) have an amphi-atlantic distribution, while the other two species are restricted either to the North-American East coast (*J. posthirsuta*) or the European coasts (*J. forsmani*).

Nearly all demographic analyses of the four species that are found on the European coasts have reported female-biased sex ratios in adults in natural populations (Cléret, 1966b; Jaźdźewski, 1969; Jones and Naylor, 1971; Naylor and Haahtela, 1967; Naylor et al., 1961; Piertney and Carvalho, 1996; Solignac, 1976) with male proportions locally as low as 0.07 (*J. ischiosetosa* in the UK, Jones and Naylor, 1971). To our knowledge no such estimations have been reported for *J. posthirsuta*.

Two studies examined the sex ratio in offspring reared in the laboratory (with low mortality, sex ratio at maturity is informative of sex-ratio at birth). In contradiction with the results from adults in natural populations, these two studies found unbiased offspring sex ratio in species *J. albifrons* (Cléret, 1966b; Piertney and Carvalho, 1996), *J. forsmani*, and *J. ischiosetosa* (Cléret, 1966b). Solignac (1978, p. 89) also reported that he did not observe a biased sex ratio in young adults reared in the

95 laboratory. However, the figures reported by this author suggest a slight excess of females at birth in
96 *J. ischiosetosa* (*r*=0.42, binomial test *p*=0.02, from table 4.1 in Solignac 1978: 89). In addition, a
97 notable exception concerns a population from Normandy, France, where a subset of *J. praehirsuta*
98 females were shown to produce an excess of female offspring (Cléret, 1966a). The author concluded
99 that a genetic factor lethal for the males was segregating in this population.
100 Observations of even numbers of males and females at birth are compatible with the genetic
101 sex-determination system that was identified for the four European species (males ZZ, females
102 ZW1W2, Staiger and Bocquet, 1954; Staiger and Bocquet, 1956, again to our knowledge this system
103 has not yet been confirmed in *J. posthirsuta*). Accordingly, all four European species of the *Jaera*
104 *albifrons* group have long been proven to be strictly gonochoric (no sex-change, which is a strategy
105 found in some other isopods, as reviewed in Policansky, 1982; Poore and Bruce, 2012). Moreover,
106 genetic sex determination has been confirmed through repeated karyotype studies (Lécher, 1967;
107 Lécher and Prunus, 1971) and molecular linkage maps (AFLP: Mifsud, 2011, and RAD-seq genotyping:
108 Ribardière et al. unpublished). One study also found sex determination in species *J. albifrons* to be
109 unaffected by strong variations in temperature conditions (Piertney and Carvalho, 1996).
110 Several ideas have been put forward to explain why adult females are systematically more
111 abundant than adult males in natural populations. First, males are smaller and less conspicuous than
112 females, meaning that they could simply be missed during collection in the field (Cléret, 1966b).
113 However, sex ratio investigations based on a careful dedicated sampling consistently found female
114 biases (Jaźdźewski, 1969; Naylor et al., 1961; Piertney and Carvalho, 1996). Second, it has been
115 suggested that males have a shorter lifespan than females (Jaźdźewski, 1969; Solignac, 1976; Steele
116 and Steele, 1972), although the only data available, obtained in laboratory conditions, suggest
117 otherwise (Solignac, 1976, *J. albifrons* and *J. ischiosetosa* males both had better survival than
118 females). Finally, strong sex ratio biases could be driven by sex ratio distorters such as mitochondrial
119 variants or cytoplasmic microorganisms (reviewed in Duron et al., 2008; Duron and Hurst, 2013;
120 Jaenike, 2001; Werren et al., 2008). In isopods in particular, *Wolbachia* is the most frequent inherited

bacterium that can manipulate reproduction of its host. Yet an effect of sex ratio distorters would be visible not only at the adult stage in natural populations but also in young adults reared in the laboratory. Such effects have not yet been observed (Cléret, 1966b; Piertney and Carvalho, 1996) except in some specific populations of *J. praehirsuta* (Cléret, 1966a) and perhaps *J. ischiosetosa* (Solignac, 1978).

In summary, sex ratio biases in the *Jaera albifrons* complex are intriguing, and the causes of female excesses in adults and perhaps in some cases in offspring are unresolved. In addition to sex ratio biases, another reason to investigate whether *Wolbachia* endosymbionts are present in the *Jaera albifrons* complex is that they could play a role in reproductive isolation. Species in this complex are isolated by a combination of ecological isolation, sexual isolation, and genetic incompatibilities (reviewed in Mifsud, 2011; Ribardière et al., 2017; Solignac, 1981) so that they generally coexist without hybridization. But in some instances, local populations undergo hybridization (Solignac, 1969a, b; Solignac, 1978). Species *J. albifrons* and *J. praehirsuta* are particularly interesting in this respect as replicate mixed populations show varying degrees of introgressive hybridization (Ribardière, 2017; Ribardière et al., 2017). It would be important to know if *Wolbachia* may play any role in this variation. Interestingly, the *J. praehirsuta* broods showing aberrant sex ratios as observed by Cléret (1966a) came from a population with introgressive hybridization between *J. praehirsuta* and *J. albifrons* (Solignac 1969a, Ribardière et al. 2017).

Bouchon et al. (1998) found no *Wolbachia* in *J. albifrons*, but it could have been due to sampling insufficiency (three individuals were tested). Recently, Wenzel et al. (2018) performed an analysis of the microbiome of the four European species of the *Jaera albifrons* complex using bacterial 16S rDNA sequencing in populations from Scotland. None of the bacterial 16S sequences that they identified belonged to the *Wolbachia* group. Here we had two objectives. Our first objective was to compare sex ratios at birth *vs* adult stage in the four European species of the *Jaera albifrons* complex. For that, we reanalysed data from a large number of broods reared in the laboratory as part of an ongoing project on speciation in the *Jaera albifrons* complex (Ribardière et

al., 2017). Although adult sex ratios have been well documented by others, for comparison with our brood data we also estimated sex ratios in natural populations using a dedicated sampling effort in the region where most of our brood data came from. Our second objective was to screen all five species of the complex with a targeted assay for the presence of *Wolbachia* endosymbionts using several gene targets and populations of various geographic origins. We focused particularly on the *J. albifrons* / *J. praehirsuta* pair in regions with varying degrees of reproductive isolation. With this, our overarching goal was to test whether *Wolbachia* may or may not be involved in sex ratio biases and reproductive isolation in the *Jaera albifrons* complex.

2. Methods

2.1 Study system and general strategy

The five species of the *Jaera albifrons* group are found mid- to upper-shore, where they can locally show some differential preferences in substrate (under pebbles or on seaweeds), position in the intertidal zone, salinity, and exposure (Bocquet, 1953; Jones, 1972; Naylor and Haahtela, 1966). Individuals from the different species have the same general morphology, with males (2-3 mm) smaller than females (5 mm). Males from the five species differ only in the number and position of spines and setae that they use to court females (Bocquet, 1953), and females cannot be distinguished based on morphology. Development is direct, there is no pelagic larval stage, and offspring measure ca. 0.5 mm when they are released. Individuals become sexually mature within 4 to 5 weeks and can then be sexed based on praeoperculum differentiation (e.g. Solignac, 1979). We define sex ratio (*r*) as the proportion of males in a sample.

Our sex ratio analyses are based on two classes of data. First, we determined the sex of adult individuals sampled in natural populations. These analyses, based on a small number of sampling sites, were used to check if our study populations conform to the well-described sex ratio biases reported in the literature. Second, we used a much larger dataset to analyse sex ratios in broods reared in the laboratory. When survival in the laboratory is high (see results and discussion), then the

sex ratio measured at least five weeks after birth is a good proxy for the sex ratio at birth, which has been less well documented than adult sex ratios and brings complementary information. In addition to sex ratio analyses we used a multi-target molecular approach to search for *Wolbachia* in a large number of individuals from different species and geographic origins.

2.2 Adult sex ratio in natural populations

Because males of all four European species of the *Jaera albifrons* group are smaller than females and can thus be more easily missed during field sampling, we selected four sampling sites/habitats (Table 1) where we carefully sampled all individuals in a delimited area. In our primary study region (Brittany, western France), species *J. albifrons*, *J. ischiosetosa*, and *J. forsmani* live under rocks, while *J. praehirsuta* is found mainly on *Fucus vesiculosus* and *Ascophyllum nodosum* seaweeds (Bocquet 1953, Ribardière et al. 2017). To estimate sex ratio we thus sampled all individuals found on a limited number of rocks or algae in each site (5-15 pebbles or stones of different sizes or a random sample of algae typically contained within 10 m^2, depending on local density). All individuals were brought back to the laboratory where they were sexed and males were identified based on their secondary sexual characters. The four sampling site/habitat combinations were previously known to shelter a single species, meaning that there would be little risk that the females (for which species cannot be identified from morphological characters) could belong to two different species (see results). Binomial tests were used to test for a departure from even sex ratio (all analyses performed in R, R Core Team, 2016).

2.3 Sex ratio in broods reared in the laboratory.

Raising individuals from birth to sexual maturity in the laboratory gives access to sex ratio under controlled conditions, and, if survival has been high enough (see results), to estimate sex ratio at birth. In the course of an ongoing project on the *Jaera albifrons* complex we raised a large number of broods in standardized laboratory conditions. These data were used to count the number of males

and females in each brood and compare sex ratio estimates across broods and populations. Rearing conditions are detailed in supplementary material.

All broods were produced by females maintained in the laboratory, but within two different experimental frameworks. First, we reared broods produced by females that came directly from the field. This is possible because females store sperm and can thus produce offspring in the laboratory in absence of males (each female was kept in an separate well and was thus never in contact with males). Within this framework, we have no information on the father of the offspring, the age of the mother, and little *a priori* information, if any, on the female's species (this was later determined from the morphological characters borne by male offspring of each female).

Second, we reared broods produced through controlled experimental crosses featuring parents that had been reared in captivity. In that case both the mother and father of each brood are known and identified, and the parents were virgin before the experiment (i.e. in most cases we analysed their first brood, or we knew how many broods were produced before). Such controlled crosses were run only with *J. albifrons* and *J. praehirsuta*. Since we did not detect any significant difference in sex ratio between the broods produced by females caught in the wild *vs* those from controlled experimental crosses (supplementary material Figure S1), we did not separate these two types of data for sex ratio analyses (unless stated otherwise).

Overall, we used data from 375 broods reared in the laboratory between 2013 and 2016. A large fraction of the data came from a region of France where we have been studying natural hybridization between *J. albifrons* and *J. praehirsuta* (region Normandy, Ribardière et al., 2017). These data (243 broods) were analysed separately (next section). The other fraction corresponds to 132 broods from four species that were originally sampled in region Brittany, where no hybridization has been detected (Ribardière et al., 2017): *J. albifrons* (*n* = 72 broods), *J. praehirsuta* (*n* = 25), *J. ischiosetosa* (*n* = 12), and *J. forsmani* (*n* = 23). We used these data to estimate brood sex ratio and compare it with adult sex ratio estimated in natural populations from Brittany (as described above).

Sex ratio in case of introgressive hybridization between J. albifrons and J. praehirsuta

Two analyses were performed to investigate the consequences of introgressive hybridization on sex ratio in *J. albifrons* and *J. praehirsuta*. First, we compared the sex ratio in broods from each species in regions Brittany (no hybridization) *vs* Normandy (hybridization). For that we used broods from females sampled in the wild (*J. albifrons* in Brittany, *n* = 34 broods, Normandy, *n* = 22; *J. praehirsuta* in Brittany, *n* = 15, Normandy, *n* = 39). Second, we compared the sex ratio in broods resulting from controlled intra- and inter-specific crosses. For that we used intra-specific *J. albifrons* crosses (*n* = 131 broods), intra-specific *J. praehirsuta* crosses (*n* = 134), first-generation hybrids (*n* = 17), and backcrosses (F1 hybrid females crossed with either *J. albifrons* or *J. praehirsuta* males, *n* = 58). Generalized linear models with a logit link function and binomial errors were used to test for differences in sex ratio amongst categories.

2.4 PCR detection of Wolbachia

The presence of *Wolbachia* endosymbionts can be detected by PCR amplification using host DNA extracts (potentially containing co-extracted DNA from endosymbionts) with *Wolbachia* specific primers (Simoes et al., 2011).

A total of 817 individuals belonging to the five species of the *Jaera albifrons* complex, including 321 females and 496 males, were tested. We used samples from 9 populations from France, 2 populations from Quebec (Canada), 1 population from the Isles of Scilly (United-Kingdom), and 1 population from Tromsø (Norway), as detailed in supplementary Table S1. The samples from France included *J. albifrons* and *J. praehirsuta* from sites with and without hybridization, as described above for the sex ratio analyses. In addition, because the presence of *Wolbachia* has been investigated in few marine species, we also analysed 34 individuals of 6 marine isopod and amphipod species (Table S2).

Total DNA (from *Jaera spp.* and potential *Wolbachia sp.*) was extracted using either a NucleoSpin Tissue kit (Macherey–Nagel) or a salt protocol (detailed in supplementary material). To

check the general quality of DNA extracts, we used a subset of 90 randomly chosen individuals to amplify 24 *Jaera albifrons* microsatellites (Ribardière et al., 2015). In addition, a DNA extract from *Oniscus asellus* (common woodlouse) known to be infected by *Wolbachia* was used as positive control to check if *Wolbachia* was correctly detected by the different methods described below.

Three different loci were targeted to increase our detection ability and confidence (details in Table 2). First, we used the *wsp* gene (*Wolbachia* surface protein), which encodes a major cell surface coat protein and is one of the most common targets for *Wolbachia* PCR detection (Braig et al., 1998; Zhou et al., 1998). We used four distinct *wsp* protocols (*wsp*-1, *wsp*-2, *wsp*-L, and *wsp*-J, Table 2) with three different pairs of primers, including newly developed primers JwspF 5' CGTTCGTTTACAATACAACGGTGA 3' and JwspR 5' AACCGAAGTAACGAGCTCCA 3'. These new primers were designed from a *Wolbachia* sequence that we obtained in this study from two individuals of the *Jaera albifrons* complex (see results). Second, the ribosomal 16S-2 marker was also chosen because it is a universal barcoding locus for bacteria identification that is expected to produce a strong signal (Simoes et al., 2011). Finally, we also used the *fbpA* primers that amplify a region of the fructose-bisphosphate aldolase gene (Baldo et al., 2006). This method lacks specificity but it can be more sensitive (Simoes et al., 2011). Polymerase Chain Reaction (PCR) conditions are detailed in Tables S3 and S4. PCR products were electrophoresed in 1.5% agarose gels stained with ethidium bromide and visualized under UV light. Some individuals were tested several times with different primers, bringing the total number of tests to 1692 (or 2445 when including individuals tested several times with the same protocol). A re-amplification based on a subset of PCR products for the *wsp* gene was also performed for 423 samples to enhance detection ability. Details of analysed samples (primers used, species, sex, origin) are given in supplementary materials (Table S1).

The large majority of these tests produced no amplified products (see results), but all amplifications resulting in a single band around the expected size were directly sequenced. Overall, 98 PCR products (in addition to the positive control) were sent for sequencing to Eurofins Genomics (Ebersberg, Germany). The sequences obtained were assembled and checked with the CodonCode

277 Aligner software (CodonCode corporation, Centerville, MA) and then compared to the GenBank
278 Nucleotide database using BLAST (Basic Local Alignment Search Tool, NCBI).
279 To determine the phylogenetic position of the *Jaera*-specific *Wolbachia* sequence that we
280 found in this study (see results), we built a neighbour-joining phylogeny using a sample of related
281 sequences deposited in GenBank (with a particular focus on strains found in marine crustaceans,
282 Cordaux et al., 2012).
283
284 **3. RESULTS**
285 *3.1 Adult sex ratio in natural populations*
286 Between 64 and 115 adult individuals were sampled in each of the four populations chosen for
287 sex ratio estimates. Three out of the four European species of the *Jaera albifrons* group presented a
288 female-biased sex ratio (Table 1 and Figure 1), with *J. ischiosetosa* showing the strongest bias (20
289 males, 94 females, binomial test p-value < 0.001). *J. albifrons* and *J. forsmani* were also characterized
290 by a significant excess of females, while *J. praehirsuta* did not reveal any bias (30 males, 34 females,
291 $p = 0.71$). All males sampled in a site/habitat combination belonged to a single species, except for
292 three *J. praehirsuta* males that were found in the *J. albifrons* sample (that is, under rocks), in
293 agreement with the level of habitat overlap between these two species in the region sampled
294 (Ribardière et al., 2017). These males were removed from all analyses but there is a small possibility
295 that some of the females used to estimate the *J. albifrons* sex ratio were in fact *J. praehirsuta* (see
296 discussion).
297
298 *3.2 Sex ratio in broods reared in the laboratory.*
299 Using 132 broods from four species that were originally sampled in the French region Brittany
300 (i.e. where species are reproductively isolated), we raised 1349 progenies (Table 4). The average
301 survival rate in the laboratory (that is, from birth to the date when each individual was sexed) was
302 77.5%, meaning that 1046 individuals could be sexed successfully across the four species. We

observed a strong bias towards females in *J. ischiosetosa* (r = 0.29, binomial test p-value < 0.001). The other three species did not show any significant sex bias (Table 3 and Figure 1). The distribution of sex ratio per brood is shown in supplementary material Figure S2.

In the case of *J. ischiosetosa*, we raised 130 offspring from 12 broods with a survival rate of 85%. With 20 dead out of 130 individuals, sex-biased mortality cannot account for the sex ratio bias that we observed. Even if all dead individuals were males, then the sex ratio at birth would still be significantly biased (52 theoretical males, 78 females, binomial test p-value = 0.028). The same reasoning applies to all four species and we consider laboratory sex ratio as a good proxy for sex ratio at birth (Figure 1).

3.3 Sex ratio in case of introgressive hybridization between J. albifrons and J. praehirsuta

First, we compared the sex ratio in broods produced by females *J. albifrons* and *J. praehirsuta* in Brittany (no hybridization) and Normandy (introgressive hybridization). For this analysis we had the sex of 798 individuals (out of 1070 offspring isolated) and found no significant bias in sex ratio within each species in each region (all binomial test p-values > 0.05) and no significant differences across species and regions (GLM p-values > 0.05 for both factors and their interaction). These results are shown in supplementary material Figure S3.

We came to the same conclusion when analysing broods from experimental crosses featuring *J. albifrons*, *J. praehirsuta*, F1 hybrids, and backcross hybrids (Figure 2, 1902 sexed individuals out of 2744 reared offspring). Again we found no significant deviation from even sex ratio within each class (all binomial test p-values > 0.05) and no significant difference between classes (GLM p-value > 0.05).

3.4 PCR detection of Wolbachia

We searched for *Wolbachia* in the *Jaera albifrons* complex by conducting 2,445 tests involving 817 individuals (see supplementary material, Table S1). Overall, 731 individuals were tested more than once, among which 232 have been tested with at least 2 different protocols. None of our

329 negative controls showed amplification signals, whilst our positive control (DNA extract from a
330 *Wolbachia*-infected woodlouse) was correctly and constantly amplified by all methods. Our *Jaera*
331 microsatellite markers amplified well, suggesting that there was no obvious problem with the
332 general quality of the DNA extraction protocols (linked e.g. with PCR inhibitors).
333 With the *fbpA* and 16S-2 protocols no amplification of expected size was detected for any of
334 the tested individuals (*n*=47 individuals tested for each marker). The wsp-1 and wsp-2 protocols
335 produced a weak amplification signal for 6% (*n*= 6 out of 95) and 3% (*n*=8 out of 252) of the tested
336 individuals, respectively. Re-amplification attempts for 272 of these PCR products (details in Table
337 S1) did not produce any amplicon corresponding to a *Wolbachia* sequence. By contrast, the sequence
338 obtained with our positive control hit the expected *Wolbachia* sequence (accession number
339 **AJ276601.1**).
340 The more sensitive wsp-L protocol, tested on 615 individuals, produced 62 PCR products
341 showing a single band with amplification size close to that expected. These 62 PCR products were
342 directly sequenced, and two of them were identical and showed >99% identity with the top
343 *Wolbachia wsp* hit in Genbank (3 differences out of 540 nucleotides). We deposited this new
344 *Wolbachia* sequence in Genbank with accession number **MH121068**. Here again, re-amplification
345 attempts of 102 individuals did not lead to the discovery of further *Wolbachia* hosts.
346 The new primers specifically designed from the *Wolbachia* sequence that we isolated as
347 described above were used with 129 individuals (protocol *wsp*-J). None of them produced
348 amplification signals (including the two individuals that were previously found to be infected with
349 *Wolbachia*). Re-amplification of a subset of 40 PCR products did not yield any additional result.
350 Finally, we used the newly designed primers to re-amplify 53 PCR products previously
351 amplified with the *wsp*-L primers (chosen because they produced a signal of expected size). Twelve
352 of these re-amplifications produced a strong band at the expected size, and eight of them appeared
353 to be *Wolbachia* sequences, including the 2 individuals previously detected as positives. All eight
354 individuals shared the same *Wolbachia* sequence (accession number **MH121068**). They were all

355 females: 1 supposed *J. praehirsuta* (because found on seaweeds in region Brittany, Ribardière et al.,
356 2017), and 4 *J. albifrons*, 2 *J. praehirsuta* and 1 female of unknown species from French region
357 Normandy.

358 The phylogeny that we built using closely related sequences indicated that our discovered
359 *Wolbachia* strain belongs to the Rug group of *Wolbachia*, within the B supergroup (Figure 3, Cordaux
360 et al., 2001). Interestingly, the Rug group happens to be the main *Wolbachia* group known to include
361 strains infecting marine arthropods (Cordaux et al., 2012).

362 Finally, the presence of *Wolbachia* was not detected in any of the other isopod and amphipod
363 species that were tested in this study (Table 3).

364

365 **4. DISCUSSION**

366 Unexpectedly, the four European species of the *Jaera albifrons* complex followed one of three
367 distinct sex ratio regimes. Two species (*J. albifrons* and *J. forsmani*) were found to have balanced sex
368 ratios at birth (as deduced from the sex ratio in young adults and low mortality in laboratory
369 conditions), but a female-biased adult sex ratio in natural populations (Table 1 and Figure 1). This
370 result confirms previous findings for these two species (Cléret, 1966b; Piertney and Carvalho, 1996).
371 More surprising results came from *J. ischiosetosa*, which showed a strong bias towards females both
372 at the offspring and adult stages, and *J. praehirsuta*, which showed no bias at any stage (Table 1 and
373 Figure 1).

374 The case of *J. ischiosetosa* is the most interesting, as it indicates that there is a mechanism in
375 this species that drives a female-biased sex ratio very early in the life cycle. Moreover, this result
376 disagrees with the only other report of sex ratio at birth in this species (Cléret, 1966b), suggesting
377 that there is variation in the sex ratio at birth between populations, or through time (see also
378 Solignac, 1978, p. 89). This points towards endogenous factors such as mitochondrial variants,
379 meiotic drive sex ratio distorters, or reproductive parasites. Here we have performed an intensive
380 survey for the presence of *Wolbachia* endosymbionts, which were an obvious candidate for

reproductive manipulation in isopods showing an excess of females. We did not find any trace of *Wolbachia* in 77 *J. ischiosetosa* individuals using several different protocols that targeted the *wsp* region (Table S1). This targeted assay involved the mothers of seven of the 12 broods that were analysed for that species (brood sex ratio from 0.08 to 0.43, Figures 1 and S2). We conclude from these observations that *Wolbachia* is either absent or has a low prevalence in *J. ischiosetosa* and thus cannot be accountable for the excess of females observed in this species.

Other endosymbiotic manipulators of sex (such as bacteria from groups *Cardinium*, *Rickettsia*, and *Spiroplasma*, or microsporidia) could be involved. In their microbiome study, (Wenzel et al., 2018) found evidence for the presence of *Rickettsiacea* in *J. ischiosetosa* females (and not in males), but in minute quantities (1.16% of the 16s sequences obtained for a sample of *J. ischiosetosa* females, M. Wenzel pers. comm.). The best way to test for this hypothesis will be to estimate sex ratio in broods reared in laboratory with and without broad-spectrum antibiotic treatment (Bordenstein et al., 2001; Breeuwer and Jacobs, 1996). Alternatively, the hypothesis of sex ratio distorters borne on the sex chromosomes could be tested using controlled crossing experiments. Finally, although it seems an unlikely hypothesis (ruled out in species *J. albifrons*, Piertney and Carvalho, 1996), an effect of the environment on sex determination could be further checked specifically in species *J. ischiosetosa*.

The three other species analysed here did not show any bias in sex ratio at birth, but two of them (*J. albifrons* and *J. forsmani*) had female-biased sex ratios at the adult stage in natural populations, in agreement with all previous sex ratio reports for these two species. Hence for these two species at least, males must have lower survival than females in nature. This sex-linked difference in survival is not seen in the laboratory (Piertney and Carvalho, 1996; Solignac, 1978, p. 89), which suggests that it depends on environmental conditions encountered in natural settings. Excluding environmental effects on sex determination (Piertney and Carvalho, 1996), the earlier mortality of males could be due to a difference in costly activities between males and females. In particular, one can imagine that males wander more than females to search for potential mates.

Moving from one shelter to another could be a risky business in species that live under pebbles and stones on coarse sand or gravel. This sex-specific behaviour could also be linked to a more general pattern of male-biased dispersal. In both cases, it could result in a higher mortality of males seen in nature but not in the laboratory. Mortality risks associated with sex-specific behaviours such as mate seeking or dispersal have been found to impact adult sex ratios in other animal groups (e.g. reviewed in Donald, 2007; Székely et al., 2014).

Interestingly, *J. ischiosetosa* not only showed a female bias at birth but it was also the species with the strongest bias in adults from natural populations in this study (Table 1 and Figure 1) and other works (e.g. Jones and Naylor, 1971). Here we found that the bias in adults (r=0.18) was significantly stronger than in offspring reared in the laboratory (r=0.29, binomial proportions test p=0.03), suggesting that the factor that causes the female bias at the adult stage in other species may also be acting in *J. ischiosetosa*.

Finally, the fourth species studied here (*J. praehirsuta*) did not show any bias at the offspring and adult stages (Table 1 and Figure 1). The most obvious difference between this species and others is that it lives essentially on seaweeds (in our study area). It is thus possible that the male-biased mortality discussed above is habitat-dependent. Since ecological conditions vary widely across the distribution of all species of the *Jaera albifrons* complex, one straightforward way to test this hypothesis is to compare sex ratios in populations in different ecological contexts (especially different substrate types where one can hypothesize that exploratory movements are more or less facilitated). For instance, while *J. praehirsuta* is dwelling on seaweeds in our study area (French region Brittany), it is found under pebbles in other areas such as region Normandy. There, this species is found mixed with *J. albifrons*, with which it hybridizes (Ribardière et al., 2017), making it more difficult to estimate specific sex ratios in nature (also because females cannot be identified unless they are kept in the laboratory until they produce offspring and these offspring are reared for long enough that the males can be identified based on their secondary sexual traits). Nonetheless, the available data for such mixed populations occupying stones and pebbles strongly suggest that the

433 sex ratio is female-biased in *J. praehirsuta* (e.g. 61 males for 138 females of a mixed *J. albifrons*/*J.*
434 *praehirsuta* population, Ribardière et al. 2017, and the same type of observation was made in
435 populations from the UK where there seems to be no hybridization, M. Wenzel pers. comm.). Hence
436 it seems that the adult female excess is dependent upon ecological conditions, at least in species *J.*
437 *praehirsuta*.

438 Our *Wolbachia* survey involved a large number of individuals (*n*=817) from the five species of
439 the *Jaera albifrons* complex sampled in different geographic regions and tested with a variety of
440 protocols (11 protocols involving 5 different primer pairs). This effort led to the discovery of a new
441 *Wolbachia* strain (*wsp* sequence deposited in Genbank under accession number **MH121068**) that
442 was detected in *J. albifrons* and *J. praehirsuta*. This adds these two species to the limited list of
443 marine crustaceans known to be infected by *Wolbachia* (Bouchon et al., 1998; Cordaux et al., 2012).
444 Our negative controls always came back negative, no *Wolbachia* gene amplification was carried in
445 our laboratory before this study, and the new sequence that we found was different from that of our
446 positive control and related to other known marine arthropod-infecting strains. Yet this result must
447 be considered with caution, as this new *Wolbachia* sequence was amplified from only eight DNA
448 extracts, nearly only using a double amplification protocol (*wsp*-L followed by *wsp*-J, see Tables 2 and
449 S1), and could not be replicated using simple-amplification protocols (even using newly designed
450 primers). We conclude that *Wolbachia* bacteria are present in at least two species of the *Jaera*
451 *albifrons* complex in French regions Brittany and Normandy, but most likely with a very small
452 prevalence (both in terms of the number of individuals infected and the concentration of bacteria
453 within infected individuals). This finding consolidates the simultaneous result obtained by Wenzel et
454 al. (2018), where bacterial 16s rDNA sequencing did not reveal any trace of *Wolbachia* in Scottish
455 populations from the four European species of the *Jaera albifrons* complex.

456 Taken together, our observations that i) *Wolbachia* was not found in the only population
457 showing a female-biased sex ratio at birth (*J. ischiosetosa*), ii) it was detected in very few individuals
458 in other species, and iii) a single strain was detected in species *J. albifrons* and *J. praehirsuta* based

459 on the *wsp* locus (and in regions with and without hybridization) lead to the conclusion that
460 *Wolbachia* bacteria most likely have no feminization or male killing effects in the *Jaera albifrons*
461 complex, and that they have also no bearing upon reproductive isolation between species within the
462 complex. Sex ratio analyses prompted us to hypothesize that some other sex ratio distorter is acting
463 in a subset of populations (such as the *J. ischiosetosa* population studied here, and perhaps the *J.*
464 *praehirsuta* population reported by Cléret 1966b), and that the ubiquitous excess of adult females in
465 nature may be due to substrate-dependent male-biased mortality.

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Research data

All data used for the brood sex ratio analyses presented in this article will be available on Dryad upon acceptance

Author contributions

Conceptualization and methodology: AR, CD-T, RC, and TB. Sex ratio data acquisition: AR, JC, JeC, CH, EK, SJ and TB. Molecular investigations: AR, JC, AD, and CD-T. Data curation: AR, JC, and TB. Writing – original draft: AR, CD-T and TB. Writing – review and editing: AR, CD-T, RC, and TB. Supervision, project administration and funding acquisition: TB. All authors have approved the final article.

Declarations of interest: none

484 **References**

485 Baldo, L., Hotopp, J.C.D., Jolley, K.A., Bordenstein, S.R., Biber, S.A., Choudhury, R.R., Hayashi, C.,
486 Maiden, M.C.J., Tettelin, H., Werren, J.H., 2006. Multilocus sequence typing system for the
487 endosymbiont Wolbachia pipientis. Appl Environ Microb 72, 7098-7110.
488 Bocquet, C., 1953. Recherches sur le polymorphisme naturel des *Jaera Marina* (Fabr.)(Isopodes
489 Asellotes) : Essai de systématique évolutive. Centre national de la recherche scientifique.
490 Bocquet, C., 1972. La speciation des *Jaera albifrons*. Etat présent des connaissances et des
491 problèmes. Fifth European Marine Biology Symposium, 131-137.
492 Bordenstein, S.R., O'Hara, F.P., Werren, J.H., 2001. Wolbachia-induced incompatibility precedes
493 other hybrid incompatibilities in Nasonia. Nature 409, 707-710.
494 Bordenstein, S.R., Werren, J.H., 1998. Effects of A and B Wolbachia and host genotype on
495 interspecies cytoplasmic incompatibility in Nasonia. Genetics 148, 1833-1844.
496 Bordenstein, S.R., Werren, J.H., 2007. Bidirectional incompatibility among divergent Wolbachia and
497 incompatibility level differences among closely related Wolbachia in Nasonia. Heredity 99, 278-287.
498 Bouchon, D., Cordaux, R., Grève, P., 2008. Feminizing Wolbachia and the evolution of sex
499 determination in isopods. Insect symbiosis 3, 273-294.
500 Bouchon, D., Rigaud, T., Juchault, P., 1998. Evidence for widespread Wolbachia infection in isopod
501 crustaceans: molecular identification and host feminization. Proceedings. Biological sciences / The
502 Royal Society 265, 1081-1090.
503 Braig, H.R., Zhou, W., Dobson, S.L., O'Neill, S.L., 1998. Cloning and Characterization of a Gene
504 Encoding the Major Surface Protein of the Bacterial EndosymbiontWolbachia pipientis. Journal of
505 bacteriology 180, 2373-2378.
506 Breeuwer, J., Jacobs, G., 1996. Wolbachia: intracellular manipulators of mite reproduction.
507 Experimental and Applied Acarology 20, 421-434.
508 Cléret, J.-J., 1966a. Etude d'un facteur polygynique chez *Jaera albifrons* Leach. (Crustacea, Isopoda).
509 Bull. Soc. lin. Normandie 7, 161-169.

510 Cléret, J.-J., 1966b. Le rapport numérique des sexes dans quelques populations naturelles de *Jaera*
511 *albirons* Leach. Bull. Soc. lin. Normandie 7, 155-161.
512 Cordaux, R., Bouchon, D., Greve, P., 2011. The impact of endosymbionts on the evolution of host sex-
513 determination mechanisms. Trends in Genetics 27, 332-341.
514 Cordaux, R., Gilbert, C., 2017. Evolutionary Significance of Wolbachia-to-Animal Horizontal Gene
515 Transfer: Female Sex Determination and the f Element in the Isopod Armadillidium vulgare. Genes-
516 Basel 8.
517 Cordaux, R., Michel-Salzat, A., Bouchon, D., 2001. Wolbachia infection in crustaceans: novel hosts
518 and potential routes for horizontal transmission. Journal of evolutionary biology 14, 237-243.
519 Cordaux, R., Pichon, S., Hatira, H.B., Doublet, V., Greve, P., Marcade, I., Braquart-Varnier, C., Souty-
520 Grosset, C., Charfi-Cheilchrouha, F., Bouchon, D., 2012. Widespread Wolbachia infection in terrestrial
521 isopods and other crustaceans. Zookeys, 123-131.
522 Donald, P.F., 2007. Adult sex ratios in wild bird populations. Ibis 149, 671-692.
523 Duron, O., Bouchon, D., Boutin, S., Bellamy, L., Zhou, L., Engelstädter, J., Hurst, G.D., 2008. The
524 diversity of reproductive parasites among arthropods: Wolbachia do not walk alone. BMC biology 6,
525 27.
526 Duron, O., Hurst, G.D., 2013. Arthropods and inherited bacteria: from counting the symbionts to
527 understanding how symbionts count. BMC biology 11, 45.
528 Fisher, R.A., 1999. The genetical theory of natural selection: a complete variorum edition. Oxford
529 University Press.
530 Hardy, I.C., 2002. Sex ratios, Concepts and research methods. Cambridge University Press, UK.
531 Hurst, G.D., Jiggins, F.M., von der Schulenburg, J.H.G., Bertrand, D., West, S.A., Goriacheva, I.I.,
532 Zakharov, I.A., Werren, J.H., Stouthamer, R., Majerus, M.E., 1999. Male–killing Wolbachia in two
533 species of insect. Proceedings of the Royal Society of London B: Biological Sciences 266, 735-740.
534 Jaenike, J., 2001. Sex chromosome meiotic drive. Annual Review of Ecology and Systematics 32, 25-
535 49.

536 Jaenike, J., Dyer, K.A., Cornish, C., Minhas, M.S., 2006. Asymmetrical reinforcement and Wolbachia
537 infection in Drosophila. PLoS Biol 4, e325.
538 Jaźdźewski, K., 1969. Ecology and Biology of Species of the j aEra Albifrons Group (Isopoda Asellota)
539 in the Bay of Puck, Polish Baltic Sea. Crustaceana 17, 265-281.
540 Jeyaprakash, A., Hoy, M.A., 2000. Long PCR improves Wolbachia DNA amplification: wsp sequences
541 found in 76% of sixty-three arthropod species. Insect Mol Biol 9, 393-405.
542 Jones, M., 1972. Effects of salinity on the survival of the Jaera albifrons Leach group of species
543 (Crustacea: Isopoda). Journal of Experimental Marine Biology and Ecology 9, 231-237.
544 Jones, M.B., Naylor, E., 1971. Breeding and bionomics of the British members of the Jaera albifrons
545 group of species (Isopoda: Asellota). Journal of Zoology 165, 183-199.
546 Lécher, P., 1967. Cytogénétique de l'hybridation expérimentale et naturelle chez l'isopode *Jaera*
547 (*albifrons*) *syei* Bocquet. Archives de zoologie expérimentale et générale 108, 633-698.
548 Lécher, P., Prunus, G., 1971. Caryologie et taxinomie de *Jaera albifrons* (crustacé, isopode),
549 populations des côtes Bretonnes. Archives de Zoologie expérimentale et générale 112, 715-730.
550 Mifsud, D.V., 2011. The genetic basis of speciation in the *Jaera albifrons* species group of intertidal
551 isopods. University of Aberdeen, p. 201.
552 Naylor, E., Haahtela, I., 1966. Habitat Preferences and Interspersion of Species within Superspecies
553 Jaera Albifrons Leach (Crustacea . Isopoda). Journal of Animal Ecology 35, 209-&.
554 Naylor, E., Haahtela, I., 1967. Quantitative ecological distribution of the Jaera albifrons group of
555 species in the Baltic. Ophelia 4, 19-27.
556 Naylor, E., Slinn, D., Spooner, G., 1961. Observations on the British species of Jaera (Isopoda:
557 Asellota). Journal of the Marine Biological Association of the United Kingdom 41, 817-828.
558 Piertney, S.B., Carvalho, G.R., 1996. Sex ratio variation in the intertidal isopod, Jaera albifrons.
559 Journal of the Marine Biological Association of the United Kingdom 76, 825-828.
560 Policansky, D., 1982. Sex change in plants and animals. Annual Review of Ecology and Systematics 13,
561 471-495.

562 Poore, C.B., Bruce, N.L., 2012. Global diversity of marine isopods (except Asellota and Crustacean
563 symbionts). PLoS One 7.
564 R Core Team, 2016. R: A language and environment for statistical computing. R Foundation for
565 Statistical Computing, Vienna, Austria.
566 Ribardière, A., 2017. Isolement reproductif et architecture génomique de la différenciation chez deux
567 espèces du complexe Jaera albifrons (isopodes marins) - Etude de populations mixtes présentant des
568 niveaux d'isolement interspécifique contrastés. Phd Thesis, UPMC.
569 Ribardière, A., Broquet, T., Daguin-Thiebaut, C., 2015. Microsatellite markers for the Jaera albifrons
570 species complex (marine isopods). BMC research notes 8, 632.
571 Ribardière, A., Daguin-Thiébaut, C., Houbin, C., Coudret, J., Broudin, C., Timsit, O., Broquet, T., 2017.
572 Geographically distinct patterns of reproductive isolation and hybridization in two sympatric species
573 of the Jaera albifrons complex (marine isopods). Ecology and evolution.
574 Rigaud, T., Moreau, J., Juchault, P., 1999. Wolbachia infection in the terrestrial isopod Oniscus
575 asellus: sex ratio distortion and effect on fecundity. Heredity 83, 469-475.
576 Rousset, F., Bouchon, D., Pintureau, B., Juchault, P., Solignac, M., 1992. Wolbachiae ndosymbionts
577 responsible for various alterations of sexuality in arthropods. Proceedings of the Royal Society of
578 London B 250, 91-98.
579 Sazama, E.J., Bosch, M.J., Shouldis, C.S., Ouellette, S.P., Wesner, J.S., 2017. Incidence of Wolbachia in
580 aquatic insects. Ecology and evolution 7, 1165-1169.
581 Simoes, P.M., Mialdea, G., Reiss, D., Sagot, M.F., Charlat, S., 2011. Wolbachia detection: an
582 assessment of standard PCR protocols. Molecular ecology resources 11, 567-572.
583 Solignac, M., 1969a. Contiguous distributions sympatry and natural hybridization in a super-species
584 Jaera albifrons Leach (isopods asellidae). Comptes Rendus Hebdomadaires des Séances de
585 l'Academie des Sciences SERIE D 268, 1610-&.
586 Solignac, M., 1969b. Hybridation introgressive dans la population complexe des Jaera albifrons de
587 Luc sur Mer. Arch Zool Exp Gén 110, 629-652.

588 Solignac, M., 1976. Demographic Aspects of Interspecific Hybridization. Oecologia 26, 33-52.
589 Solignac, M., 1978. Nature, déterminisme et origine des mécanismes d'isolement dans le complexe
590 Jaera albifrons (Isopodes, Asellotes). Phd Thesis. Paris 6, p. 232.
591 Solignac, M., 1979. Analyse expérimentale et variabilité de l'hybridation interspécifique dans le
592 complexe d'espèces affines Jaera albifrons (crustacé isopode). Archives de zoologie expérimentale et
593 générale 120, 353.
594 Solignac, M., 1981. Isolating mechanisms and modalities of speciation in the *Jaera albifrons* species
595 complex (Crustacea, Isopoda). Systematic Zoology 30, 387-405.
596 Staiger, H., Bocquet, C., 1954. Cytological demonstration of female heterogamety in isopods.
597 Experientia 10, 64-66.
598 Staiger, H., Bocquet, C., 1956. Les chromosomes de la super-espèce Jaera marina (F.) et de quelques
599 autres Janiridae (Isopodes Asellotes). Bull. Biol. Fr. Belg 90, 1-32.
600 Steele, D., Steele, V., 1972. The biology of Jaera spp.(Crustacea, Isopoda) in the northwestern
601 Atlantic. 1. Jaera ischiosetosa. Canadian Journal of Zoology 50, 205-211.
602 Székely, T., Weissing, F.J., Komdeur, J., 2014. Adult sex ratio variation: implications for breeding
603 system evolution. Journal of Evolutionary Biology 27, 1500-1512.
604 Taylor, D.R., 1990. Evolutionary consequences of cytoplasmic sex ratio distorters. Evolutionary
605 Ecology 4, 235-248.
606 Telschow, A., Flor, M., Kobayashi, Y., Hammerstein, P., Werren, J.H., 2007. Wolbachia-induced
607 unidirectional cytoplasmic incompatibility and speciation: mainland-island model. PloS one 2, e701.
608 Turelli, M., Cooper, B.S., Richardson, K.M., Ginsberg, P.S., Peckenpaugh, B., Antelope, C.X., Kim, K.J.,
609 May, M.R., Abrieux, A., Wilson, D.A., 2018. Rapid Global Spread of wRi-like Wolbachia across Multiple
610 Drosophila. Current Biology.
611 Vavre, F., Fleury, F., Lepetit, D., Fouillet, P., Boulétreau, M., 1999. Phylogenetic evidence for
612 horizontal transmission of Wolbachia in host-parasitoid associations. Molecular biology and
613 evolution 16, 1711-1723.

614 Wenzel, M.A., Douglas, A., Piertney, S.B., 2018. Microbiome composition within a sympatric species
615 complex of intertidal isopods (*Jaera albifrons*). PLoS One.
616 Werren, J.H., 1983. Sex ratio evolution under local mate competition in a parasitic wasp. Evolution
617 37, 116-124.
618 Werren, J.H., 1997. Biology of wolbachia. Annual review of entomology 42, 587-609.
619 Werren, J.H., Baldo, L., Clark, M.E., 2008. Wolbachia: master manipulators of invertebrate biology.
620 Nature Reviews Microbiology 6, 741-751.
621 Werren, J.H., Windsor, D.M., 2000. Wolbachia infection frequencies in insects: evidence of a global
622 equilibrium? Proceedings. Biological sciences / The Royal Society 267, 1277-1285.
623 West, S.A., Sheldon, B.C., 2002. Constraints in the evolution of sex ratio adjustment. Science 295,
624 1685-1688.
625 Zhou, W., Rousset, F., O'Neill, S., 1998. Phylogeny and PCR–based classification of Wolbachia strains
626 using wsp gene sequences. Proceedings of the Royal Society of London B: Biological Sciences 265,
627 509-515.

628

Tables

Table 1. Number of males and females in natural populations of the four European species of the *Jaera albifrons* complex. Departure from an even sex ratio (proportion of males) was tested using a binomial test within each site (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

Species	Site	Habitat	Coordinates	Males	Females	Sex ratio
J. albifrons	Lingoz	rocks	48°39’12.31"N 3°57’0.43”W	15	49	0.23***
J. praehirsuta	Lingoz	algae	48°39’12.31"N 3°57’0.43”W	30	34	0.47
J. ischiosetosa	Pempoul	rocks	48°41'16.9"N 3°57'27.6"W	20	94	0.18***
J. forsmani	Pointe Grande Grève	rocks	48°42'22.6"N 3°58'18.7"W	41	74	0.36**

Table 2. Primers used in the six protocols tested in this study. Protocols *Wsp*-1 and -2 use the same primers with different PCR conditions (see supplementary Tables S3 and S4).

Name	Primer (F/R)	Product size (bp)	Reference
Wsp-1	81F/691R	610	Zhou et al. (1998)
Wsp-2	81F/691R	650	Braig et al. (1998)
Wsp-L	LongF/LongR	657	Jeyaprakash and Hoy (2000)
Wsp-J	JwspF/JwspR	464	This study
16S-2	Wspecf/Wspcr	438	Werren and Windsor (2000)
fbpA	FbpA_F1/FbpA_R1	509	Baldo et al. (2006)

Table 3. Number of males and females obtained from broods reared in the laboratory for the four European species of the *Jaera albifrons* complex. Column "sexed" gives the number of individuals that survived and were sexed, out of the total number of offspring isolated at birth (*n*). Departure from an even sex ratio (proportion of males) was tested using a binomial test within each site (*** $p<0.001$).

Species	*n*	sexed	males	females	sex ratio
J. albifrons	655	497	240	257	0.48
J. praehirsuta	211	116	61	55	0.53
J. ischiosetosa	130	110	32	78	0.29***
J. forsmani	353	323	171	152	0.53

Figure legends

Figure 1: Sex ratio (proportion males) in the four European species of the *Jaera albifrons* complex. Grey bars indicate 95% binomial confidence intervals around the observed sex ratio. All species but *J. praehirsuta* were found to be significantly female-biased at the adult stage in natural populations (sample sizes in tables 1 and 6). Only *J. ischiosetosa* presented a female-biased sex ratio in young adults reared in the laboratory (a good proxy for the sex ratio at birth when mortality is low, as in this study).

Figure 2: Distribution of offspring sex ratio per brood in *Jaera albifrons* (*n*=131 broods), *J. praehirsuta* (*n*=134), first-generation hybrids (*n*=17), and backcross hybrids (first generation female hybrids crossed with either *J. albifrons* or *J. praehirsuta* males, *n* = 58). All broods were obtained from experimental crosses where both the mother and the father were known.

Figure 3: Neighbour joining tree of some Supergroup-B *Wolbachia* sequences, based on Kimura 2-parameters distances. Strains infecting marine hosts are represented in black, and the *Wolbachia* sequence that we found in *J. albifrons* and *J. praehirsuta* is highlighted. Other *Wolbachia* sequences identified in non-marine hosts are represented in grey. The strain that we used as a positive control is identified with an asterisk. The definition of the "RUG" group follows Cordaux et al. (2012). Bootstrap support inferred from 1000 replicates is shown when it is greater than 50%.

Figure 1

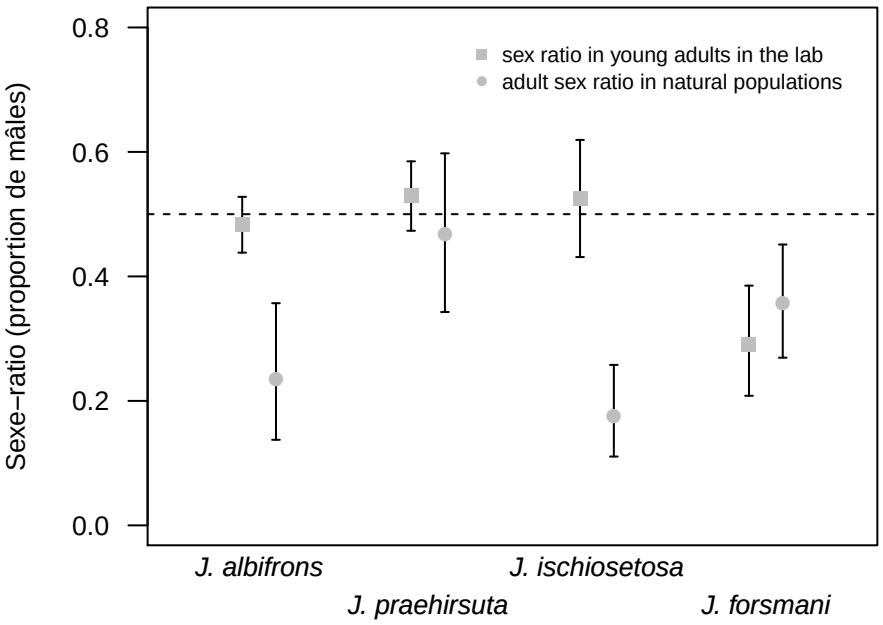

0.8
0.6
0.4
0.2
0.0
Sexe−ratio (proportion de mâles)
sex ratio in young adults in the lab
adult sex ratio in natural populations
J. albifrons
J. praehirsuta
J. ischiosetosa
J. forsmani

Figure 2

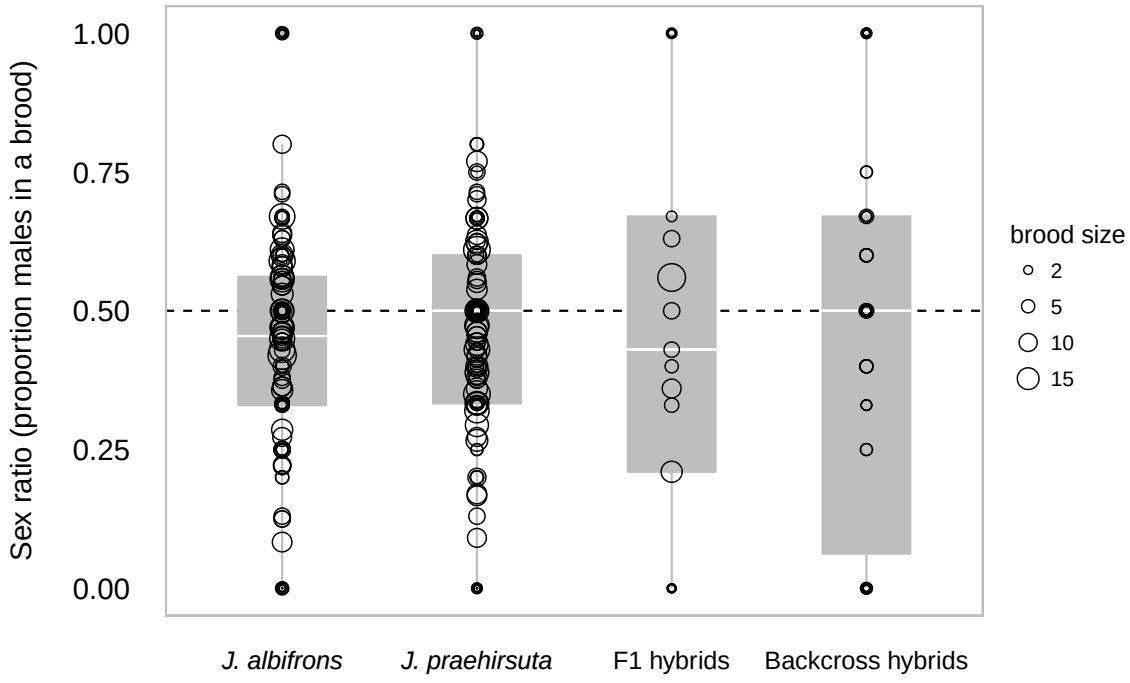
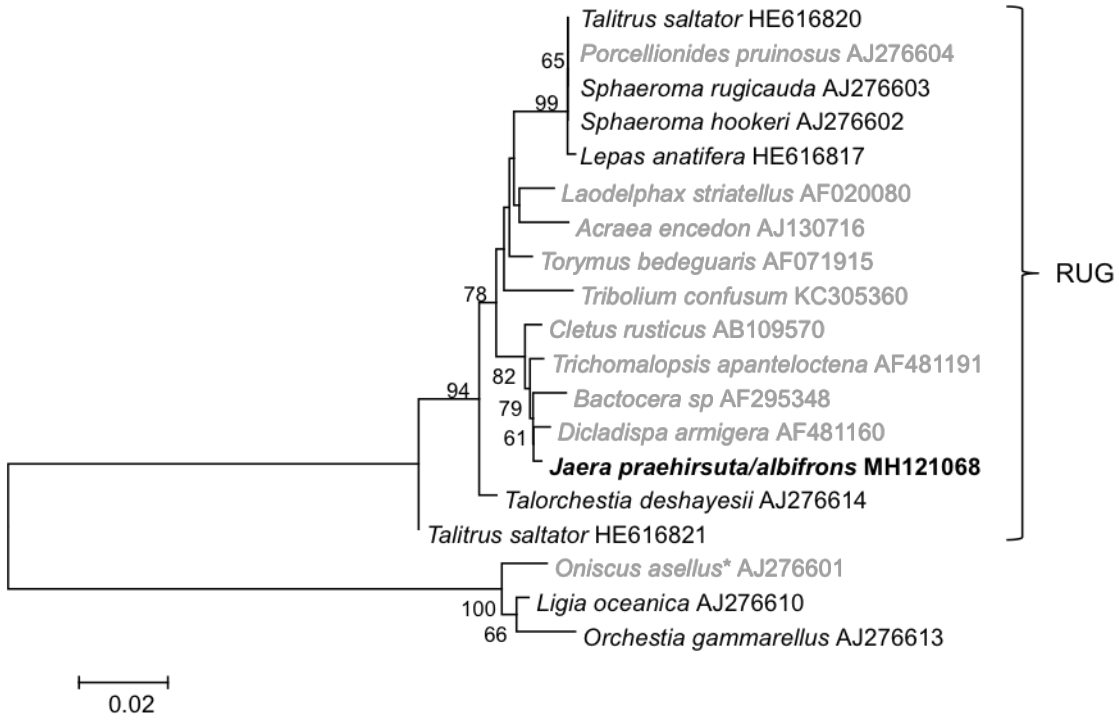

1.00
0.75
0.50
0.25
0.00
Sex ratio (proportion males in a brood)
brood size
2
5
10
15
J. albifrons
J. praehirsuta
F1 hybrids
Backcross hybrids

Figure 3


Talitrus saltator HE616820
Porcellionides pruinosus AJ276604
Sphaeroma rugicauda AJ276603
Sphaeroma hookeri AJ276602
Lepas anatifera HE616817
Laodelphax striatellus AF020080
Acraea encedon AJ130716
Torymus bedeguaris AF071915
Tribolium confusum KC305360
Cletus rusticus AB109570
Trichomalopsis apanteloctena AF481191
Bactocera sp AF295348
Dicladispa armigera AF481160
Jaera praehirsuta/albifrons MH121068
Talorchestia deshayesii AJ276614
Talitrus saltator HE616821
Oniscus asellus* AJ276601
Ligia oceanica AJ276610
Orchestia gammarellus AJ276613
65
99
78
82
94
79
61
100
66
RUG
0.02

Supplementary material

Rearing conditions

Lab conditions were as follows. All individuals were reared individually in 6-well plates (one individual per well, each well has a diameter of approximately 3.5 cm and contains ca. 10 mL of 3 µm-filtered seawater). Following the conditions described in Bocquet (Bocquet 1953: 212-213), each well contained small pieces of green algae (*Enteromorpha* sp.) and a small piece of elm leaf (elm leaves provide shelter and food, and have been used successfully for several decades by previous researchers). The plates were kept in thermostat cabinets at 17°C with an 11h/13h light/obscurity cycle and seawater was changed once a week (together with algae and leaves when needed). Embryos develop in a marsupium (brood pouch containing typically around 15 offspring) until the female releases them. At that stage the offspring measure approximately half a millimetre and closely resemble the adults (direct development, no pelagic larval stage). Offspring were isolated one by one within a few days after their release and reared individually in the same conditions as the adults, with two exceptions: seawater was not changed during the first week, and elm leaves were added only during the second week. Under these conditions, individuals can usually be sexed around the age of 4 to 5 weeks but all experiments lasted for a longer time. Since each individual was reared individually (and thus the number of offspring per brood was counted) the survival rate could be estimated for each brood.

Salt extraction protocol

Entire individuals were mashed then tissues were soaked into 500 µl of NaCl buffer (containing 1% SDS, 150 mM NaCl, 1 mM EDTA and 20 mM TRIS) with 1 mg of proteinase-K (Macherey-Nagel, Duren, Germany) and incubated at 56°C during 3h30 under agitation at 120 rpm. 0.5 mg of ribonuclease A (Macherey-Nagel, Duren, Germany) was added to each tube and incubated for 20 min under agitation at room temperature. 200 µl of NaCl buffer (5M) was then added and the tubes were

centrifuged at 16,000 g for 10 min. Supernatant was pipeted and mix to an equal volume of cold isopropanol and stored overnight at -20 °C. After centrifugation at 16,000 g for 15 min, the DNA pellet was washed with 500 µl of 80% cold ethanol and with 70% cold ethanol subsequently. DNA pellets were then dried and again suspended in 100 µl of TE 0.1X.

Table S1. List of the samples tested with the different protocols

location	species	sex	num. of indiv.	*16S-2*	*Fbp-A*	*Wsp-1*	*Wsp-2*	*Wsp-L*	*Wsp-J*	*Wsp-1 Wsp-2*	*Wsp-2 Wsp-2*	*Wsp-L Wsp-L*	*Wsp-J Wsp-J*	*Wsp-L Wsp-J*	*TOTAL*
France - Brittany (5 sites)	*J. albifrons*	F	32	15	2	8	16	25	0	8	1	0	0	0	75
	J. albifrons	M	86	6	0	13	5	74	45	13	1	3	0	0	160
	J. praehirsuta	F	25	1	16	8	8	25	9	8	0	4	9	1	89
	J. praehirsuta	M	55	3	0	9	0	51	26	9	0	9	0	0	107
	J. ischiosetosa	F	33	0	0	0	6	32	0	0	2	29	0	30	99
	J. ischiosetosa	M	39	0	0	3	2	39	8	3	0	28	0	16	99
	J. forsmani	F	1	0	0	0	1	1	0	0	0	0	0	0	2
	J. forsmani	M	15	0	0	8	0	15	8	8	0	3	0	0	42
	NA	F	7	0	0	0	7	0	0	0	7	0	0	0	14
France - Normandy (2 sites)	*J. albifrons*	F	23	1	0	15	16	17	15	15	0	4	15	4	102
	J. albifrons	M	163	3	13	6	0	161	0	6	0	12	0	0	201
	J. praehirsuta	F	20	15	0	1	12	16	16	1	0	2	16	2	81
	J. praehirsuta	M	79	0	7	11	0	77	0	11	0	2	0	0	108
	J. albifrons / *J. praehirsuta* inter. morph.	M	23	2	8	0	0	23	0	0	0	1	0	0	34
	J. forsmani	M	2	0	1	0	0	2	0	0	0	1	0	0	4
	NA	F	74	1	0	0	73	4	0	0	70	0	0	0	148
England - Scilly Islands	*J. albifrons*	M	7	0	0	0	0	7	0	0	0	1	0	0	8
	J. praehirsuta	M	12	0	0	0	0	12	0	0	0	0	0	0	12
	NA	F	10	0	0	0	8	10	0	0	0	3	0	0	21
Norway (1 site)	NA	F	43	0	0	0	43	5	0	0	43	0	0	0	91
Canada - East coast (2 sites)	*J. albifrons*	M	2	0	0	0	0	2	2	0	0	0	0	0	4
	J. ischiosetosa	M	5	0	0	5	2	5	0	5	0	0	0	0	17
	J. posthirsuta	M	8	0	0	8	0	8	0	8	0	0	0	0	24
	NA	F	53	0	0	0	53	4	0	0	53	0	0	0	110
TOTAL			817	47	47	95	252	615	129	95	177	102	40	53	

Table S2. Marine isopod and amphipod species tested for *Wolbachia*

Species	Order	Number of individuals
Jaera hopeana	Isopoda	8
Jaera nordmanni	Isopoda	4
Janira maculosa	Isopoda	5
Sphaeroma serratus	Isopoda	1
Haploops nirae	Amphipoda	8
Ampelisca spinipes	Amphipoda	8

Table S3. PCR mix composition for the six protocols used in this study.

Name	MgCl2 (mM)	primers (µM)	dNTPs (mM)	Taq (U)	Template DNA (µl)	Final Volume (µl)
16S-2	1.5	0.28	0.2	1	3	20
fbpA	1.5	1	0.2	1	3	20
Wsp-1	2.5	0.5	0.25	1	3	20
Wsp-2	1.5	0.28 - 0.8	0.05	0.75	2	15
Wsp-L	2	0.5 - 1	0.2	1	0.6	20
Wsp-J	2	0.5 - 1.33	0.2	1	0.6	20

Table S4. PCR program details; T: Temperature (°C); D: Duration (sec). A touchdown program was used for 16S-2 (presented on two lines.

Name	Initial denaturation		Denaturation		Annealing		Elongation		Nb of cycles	Final elongation	
	T	D	T	D	T	D	T	D		T	D
16S-2	95	120	95	120	60	60	72	60	2	NA	NA
			95	30	60	60	72	45	35	72	300
fbpA	94	120	94	30	59	45	72	90	36	72	600
Wsp-1	94	120	94	60	55	60	72	60	35	72	600
Wsp-2	94	180	94	30	55	30	72	60	35	72	600
Wsp-L	98	30	98	15	55	20	72	60	50	72	600
Wsp-J	98	30	98	15	54	20	72	60	35	72	600

Figures

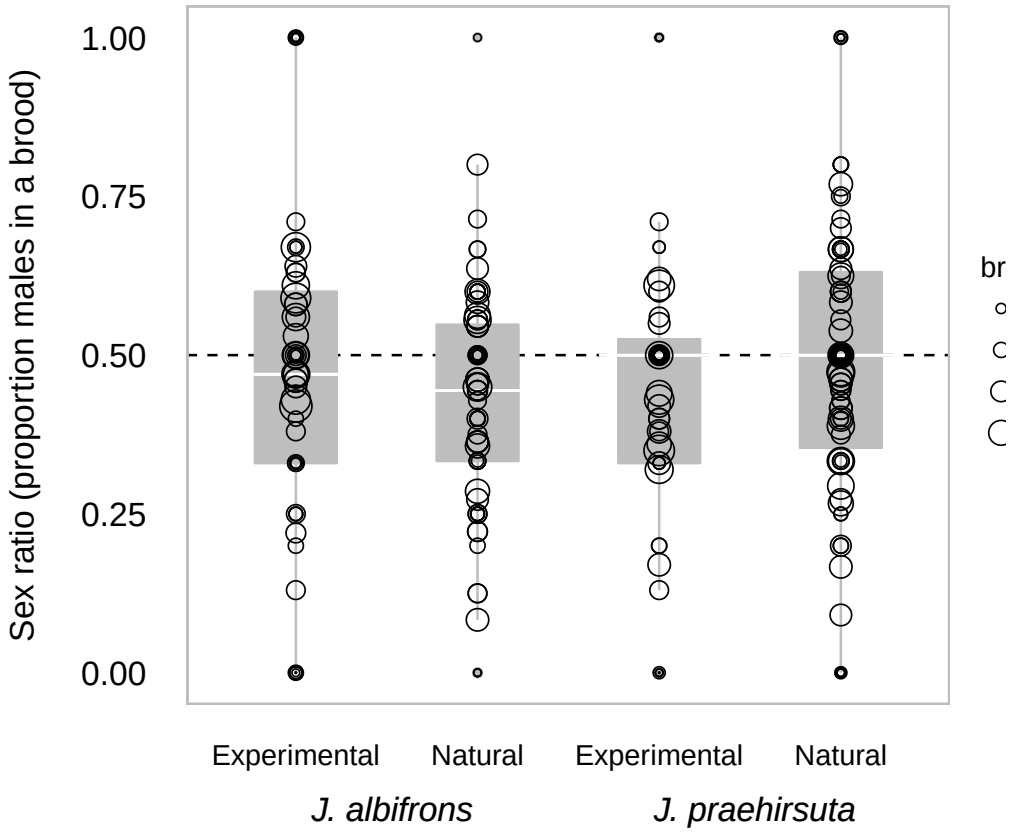


Figure S1. Distribution of offspring sex ratio per brood in *Jaera albifrons* (59 experiment
natural broods) and *J. praehirsuta* (47 and 87). Each brood was reared in the lab until in
were sexed, but the brood came either from a female sampled in the wild ("Natural") o
female that was itself born and reared in the lab until maturity and used in a controlled
experiment ("Experimental"). This figure combines data from the two regions where *J.*
J. praehirsuta were studied (Brittany and Normandy, see maintext).

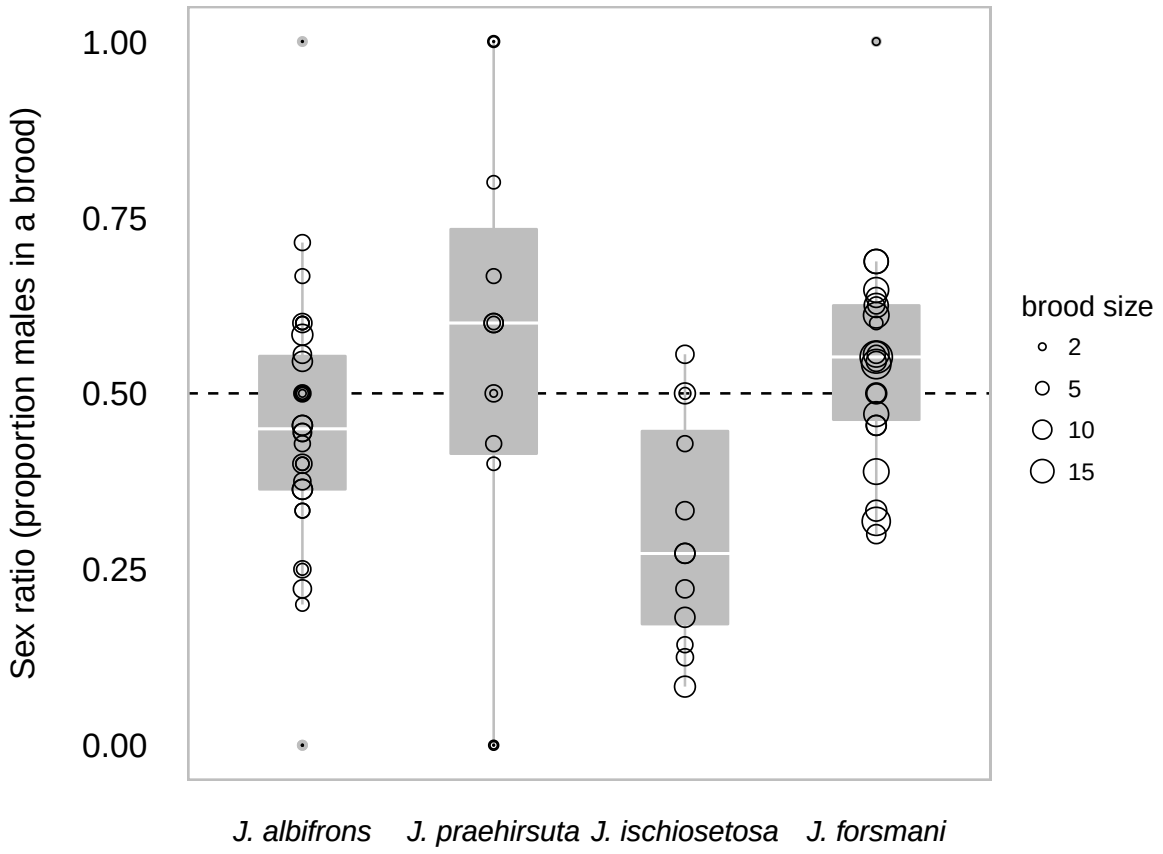


Figure S2. Distribution of offspring sex ratio per brood in *Jaera albifrons* (*n*=34 broods), *J. praehirsuta* (*n*=15), *J. ischiosetosa* (*n*=12), and *J. forsmani* (*n*=23). These broods were produced by mothers sampled from natural populations in Brittany (i.e. uncontrolled mating, fathers unknown). The average brood sex ratio in *J. ischiosetosa* is significantly biased towards females (r = 0.29, binomial test p-value < 0.001).

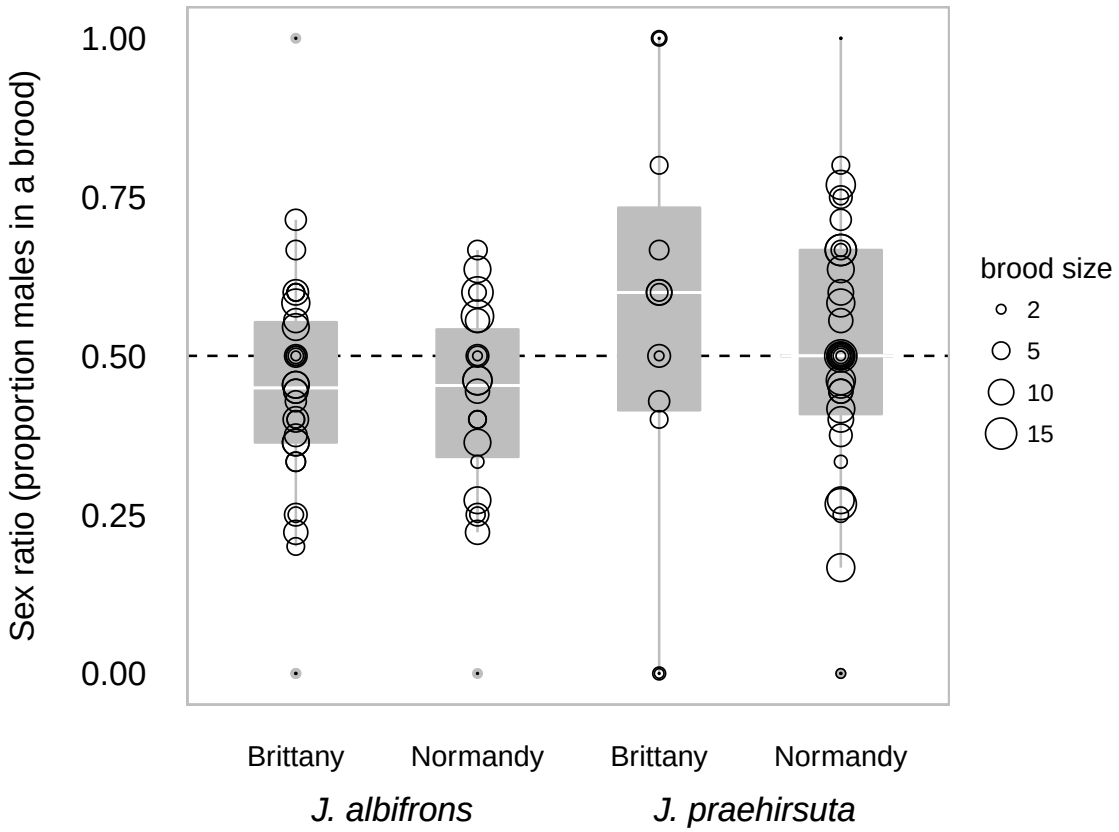


Figure S3. Distribution of offspring sex ratio per brood in *Jaera albifrons* and *J. praehirsuta* in a region where the two species are reproductively isolated (Brittany, $n_{albifrons}$= 34 broods, $n_{praehirsuta}$= 15) and in a region with introgressive hybridization (Normandy, $n_{albifrons}$= 22, $n_{praehirsuta}$= 39). These broods were produced by mothers sampled from natural populations (i.e. uncontrolled mating, fathers unknown).

References

Bocquet, C., 1953. Recherches sur le polymorphisme naturel des *Jaera Marina* (Fabr.)(Isopodes Asellotes) : Essai de systématique évolutive. Centre national de la recherche scientifique.