Experimental design impacts the vector competence of *Ornithodoros* ticks for African swine fever virus: a meta-analysis of published evaluations

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Abstract

African Swine Fever (ASF) is a highly economically devastating viral disease for swine. Soft ticks of the genus *Ornithodoros* are involved in its epidemiology, as vectors and natural reservoirs of African Swine Fever Virus (ASFV). This constitutes a significant problem as it is currently challenging to eliminate endophilous soft ticks living in inaccessible, sheltered habitats. The vector competence of *Ornithodoros* ticks for ASFV has been mainly studied by mimicking natural tick-to-pig transmission pathways through experimental infections in the laboratory. However, experimental designs are anticipated to cause significant influence on the results, owing to inherent technical limitations of the approaches. By reviewing the original research studies dating back to the 1960s on the vector competence of *Ornithodoros* for ASFV, we estimated the vector competence of 10 tick species in association with 38 viral strains resulting in 51 tick-virus associations. This assessment emphasized the extensive range of protocol designs employed and of vector competence measurements. Those experimental factors have a clear impact on the success of tick infection by ASFV. Our results offer valuable insights into how future trials can be refined by curtailing potential experimental biases. They also call for caution when interpreting conclusions drawn from studies on ASFV vector competence.

Keywords: *Ornithodoros* soft ticks, African swine fever virus, vector competence, experimental methodology, meta-analysis

Introduction

African swine fever (ASF) ranks among the most damaging viral diseases affecting swine farming. The etiologic agent is a large DNA virus belonging to the Asfaviridae family (Dixon et al., 2013). African Swine Fever Virus (ASFV) causes haemorrhagic fever in susceptible infected swine, with mortality rates of up to 100% in naïve domestic pigs. In Africa, wild suids (warthogs, and possibly bushpigs and giant forest hogs) are natural vertebrate reservoirs that are resistant to the disease (Jori et al., 2013). In Europe, wild boars are susceptible to ASFV and exhibit clinical symptoms and mortality rates comparable to those of domestic pigs. In certain countries, soft ticks of the genus *Ornithodoros* act as vectors or natural reservoirs of ASFV. The virus can persist for several years, potentially leading to epizootic outbreaks in pig farms that have become colonized by ticks, even with the implementation of ASF control measures. (i.e., pig slaughtering, disinfection, and quarantine) (Boinas et al., 2011; Jori et al., 2013). Once ASFV is introduced into a new free area where the presence of *Ornithodoros* ticks is highly suspected, as it occurred in the Caucasus in 2007 or more recently in the Caribbean, the potential for long-term persistence of ASFV in tick reservoirs and ASFV transmission via tick bites raises concern (Beltrán-Alcrudo et al., 2008; EFSA et al., 2021).

Vector competence generally refers to the vector's capacity to be infected by a pathogen, to maintain and multiply this pathogen, and finally to transmit it to a new susceptible host (Gillespie et al., 2004). The biological steps taking place within the arthropod vector can be broken down into four stages: (i) the ingestion of an infected blood meal, (ii) the infection of the vector upon crossing of its intestinal midgut by the pathogen, (iii) the persistence and multiplication of the pathogen within the vector despite the vector's immune response, and (iv) the dissemination of the pathogen inside the vector by crossing organic barriers and ultimately reaching organs implicated in the transmission to vertebrate hosts, typically the salivary glands and coxal glands. Sexual transmission of pathogens between males and females of vectors as well as

54 transovarial transmission from female vectors to their progeny can occur through the infection of reproductive organs.
55 Although not strictly included in the formal definition of the vector competence, these pathways of transmission will also
56 be considered in this review.

57 All these biological steps are observed in the interaction between ASFV and *Ornithodoros* tick although results reported
58 varied greatly between studies. In addition to historical demonstration of tick vector competence for ASFV in African *O.*
59 *moubata sensu lato* and Iberian *O. erraticus*, several other *Ornithodoros* tick species succeed to maintain or transmit ASFV
60 under experimental conditions (Mellor & Wilkinson, 1985; Endris et al., 1987; Hess et al., 1987; Endris et al., 1991). This
61 suggests that most *Ornithodoros* ticks might be able to maintain and transmit ASFV (EFSA Panel on Animal Health and
62 Welfare., 2010a). Based on available results, some researchers have proposed to predict the global role of each tick species
63 as a vector and reservoir for ASFV (Kleiboeker & Scoles, 2001; EFSA Panel on Animal Health and Welfare., 2010b; a, 2014;
64 Burrage, 2013). However, these comprehensive reports do not account for the evident disparities in vector competence
65 results, which likely rely on intricate tick-virus adaptations as proposed by Pereira de Oliveira (Pereira de Oliveira et al.,
66 2019; Pereira De Oliveira et al., 2020) and other yet-to-be-identified biological and experimental factors. No paper has
67 considered the substantial diversity of techniques employed to test vector competence except for a study on *O. erraticus*
68 infected with two Portuguese ASFV strains (Ribeiro et al., 2015). Nonetheless, the importance of experimental methodology
69 has been demonstrated in other models like mosquitoes with Rift Valley fever, Dengue, Zika or Japanese Encephalitis viruses
70 (Azar, 2019; Auerswald et al., 2021; Drouin et al., 2022). We hypothesize that the experimental design, including the choice
71 of biological materials and the methods used to infect ticks and detect the virus, is an important factor in explaining
72 variation in vector competence, in addition to the influence of tick species, ASFV strains and their combinations.

To investigate this hypothesis, a systematic review of studies published up to 2022 was conducted, examining the vector competence of *Ornithodoros* ticks for ASFV. The present paper focuses on the diverse experimental factors that may impact vector competence and determines the overall vector competence of the various associations between *Ornithodoros* tick and ASFV. We provide recommendations on how experimental trials can be refined to minimize biases and obtain more comparable and reliable results on *Ornithodoros* vector competence for ASFV.

Material and Methods

Collection of bibliographical resources

The first objective of the study was to identify the bibliographic resources related to vector competence of *Ornithodoros* ticks for ASFV, published in English, in peer-reviewed journals or under high publication standards. This was achieved following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Annex 1). Our bibliographic review was conducted until July 2022, using three different bibliographic databases: EThOS (http://ethos.bl.uk/Home.do), PubMed (http://www.ncbi.nlm.nih.gov/) and Scopus (http://www.scopus.com/). Queries were built under the keywords “African swine fever” AND “tick”. The topics not related with tick competence (e.g., immunology, genetic, vaccinology, epidemiology) were excluded during the screening phase. Then, during the eligibility phase, studies were excluded if quantitative reliable data could not be extracted from publications. Purely descriptive reviews without any original vector competence results were also excluded. Apart from published scientific papers, some authors presented their results in their PhD manuscript. These data were also considered but all duplicated results were removed to avoid biases in the analyses. Finally, the references cited at the end of the included references were checked,

91 in order to identify further relevant studies. The final list of included references that were used to extract all data in soft

92 tick vector competence for ASFV are shown in Table 1.

93

94 **Table 1 -** Included references providing original results on the vector competence of *Ornithodoros* ticks for ASFV, with number attributed to

95 each paper by year of publication.

N°	Included references
1	Parker J, Plowright W, Pierce MA. The epizootiology of African swine fever in Africa. Vet Rec. 1969;85(24):668-74
2	Plowright W, Perry CT, Peirce MA, Parker J. Experimental infection of the argasid tick, *Ornithodoros moubata porcinus*, with African swine fever virus. Arch Gesamte Virusforsch. 1970;31(1):33-50.
3	Plowright W, Perry CT, Peirce MA. Transovarial infection with African swine fever virus in the argasid tick, *Ornithodoros moubata porcinus,* Walton. Res Vet Sci. 1970 ;11(6):582-4.
4	Greig A. The localization of African swine fever virus in the tick *Ornithodoros moubata porcinus*. Arch Gesamte Virusforsch. 1972;39(1):240-7.
5	Plowright W, Perry CT, Greig A. Sexual transmission of African swine fever virus in the tick, *Ornithodoros moubata porcinus,* Walton. Res Vet Sci. 1974;17(1):106-13.
6	Groocock CM, Hess WR, Gladney WJ. Experimental transmission of African swine fever virus by *Ornithodoros coriaceus*, an argasid tick indigenous to the United States. Am J Vet Res. 1980;41(4):560-4.
7	Thomson GR. The epidemiology of African swine fever: the role of free-living hosts in Africa. Onderstepoort J Vet Res. 1985;52(3):201-9. Review.
8	Mellor PS, Wilkinson PJ. Experimental transmission of African swine fever virus by *Ornithodoros savignyi* (Audouin). Res Vet Sci. 1985;39(3):353-6.
9	Hess WR, Endris RG, Haslett TM, Monahan MJ, McCoy JP. Potential arthropod vectors of African swine fever virus in North America and the Caribbean basin. Vet Parasitol. 1987;26(1-2):145-55.
10	Endris RG, Haslett TM, Geering G, Hess WR, Monahan MJ. A hemolymph test for the detection of African swine fever virus in *Ornithodoros coriaceus* (Acari: Argasidae). J Med Entomol. 1987;24(2):192-7.
11	Hess WR, Endris RG, Lousa A, Caiado JM. Clearance of African swine fever virus from infected tick (Acari) colonies. J Med Entomol. 1989;26(4):314-7.
12	Haresnape JM, Wilkinson PJ. A study of African swine fever virus infected ticks (*Ornithodoros moubata*) collected from three villages in the ASF enzootic area of Malawi following an outbreak of the disease in domestic pigs. Epidemiol Infect. 1989;102(3):507-22.
13	Endris RG, Haslett TM, Hess WR. Experimental transmission of African swine fever virus by the tick *Ornithodoros* (Alectorobius) *puertoricensis* (Acari: Argasidae). J Med Entomol. 1991;28(6):854-8.
14	Endris RG, Hess WR, Caiado JM. African swine fever virus infection in the Iberian soft tick, *Ornithodoros* (Pavlovskyella) *marocanus* (Acari: Argasidae). J Med Entomol. 1992;29(5):874-8.
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16	Endris RG, Haslett TM, Hess WR. African swine fever virus infection in the soft tick, *Ornithodoros* (Alectorobius) *puertoricensis* (Acari: Argasidae). J Med Entomol. 1992;29(6):990-4.

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96

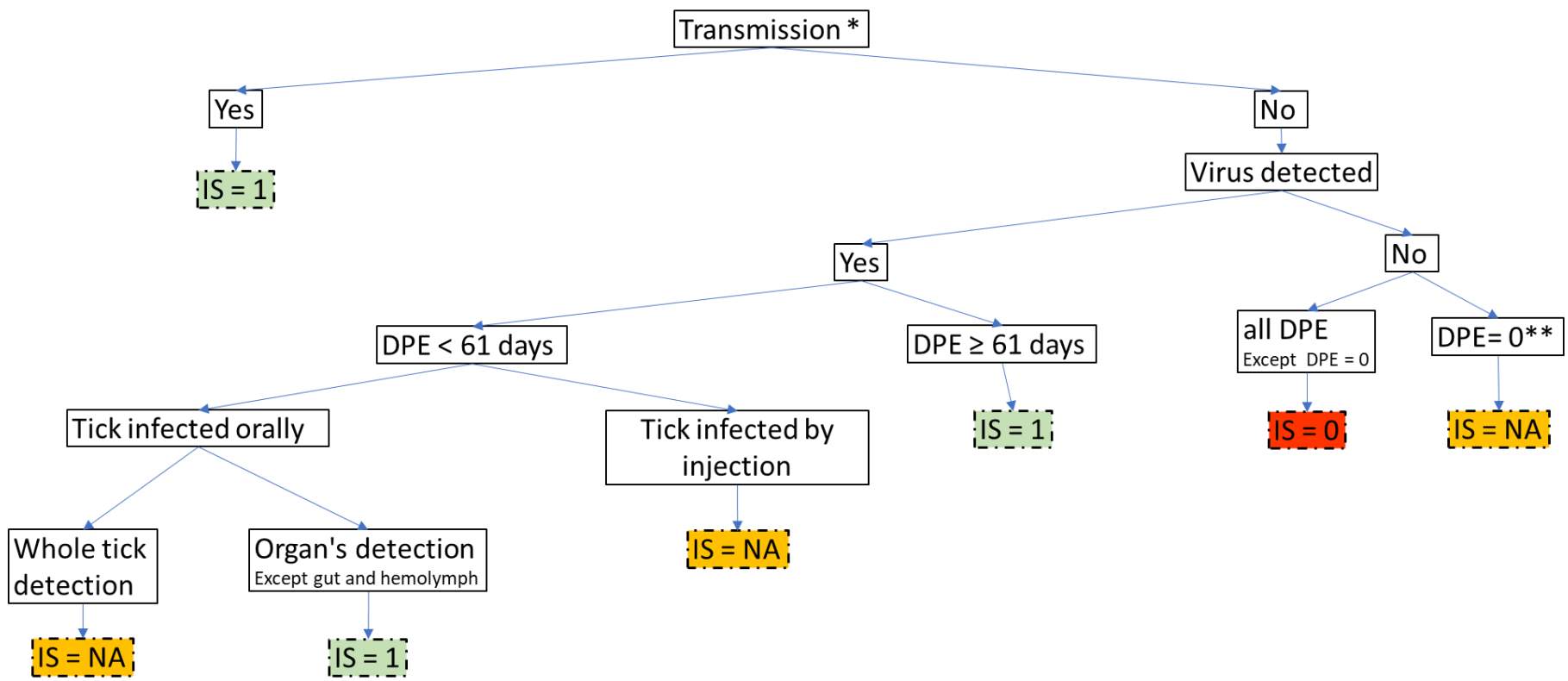
97 *Extraction of data about tick competence from bibliographical resources*

98 Bibliometric general information on authors and years of publication were collected to describe the general interest in
99 tick vector competence for ASFV and to identify scientific experts. We considered the experts as the persons in first and
100 last position of the included references. Information on tested *Ornithodoros* tick-ASFV associations was systematically
101 reported. A challenge was to deal with missing or incomplete data for ASFV strains, as well as the ambiguities in tick species
102 identification.

103 Regarding virus, we recorded the strain, the genotype (on the basis of p72 gene sequences, Qu *et al*. 2022), the
104 geographical origin, and the host (vertebrate animals or ticks) from which the ASF virus was isolated. The original names of
105 some ASFV strains were retrieved by crossing information from the literature, according to known authors' collaborations,
106 or by directly contacting the authors. When the determination of strains remained impossible, the strain was identified by
107 indicating the country where the ASFV strain was isolated, the year of the study, and a letter if duplicates existed. One
108 exception was a strain used to infect *O. turicata* (Hess et al., 1987) without any indication of the country of origin which
109 was named Unknown. Six recombinant ASFV strains, genetically modified and obtained from two natural strains(Burrage
110 et al., 2004; Nix, 2006), were excluded from this review since they cannot infect ticks in nature. Genotypes were not
111 available for some strains of ASFV, but they could be inferred based on their geographical origin and ASFV genotype
112 distribution published by Lubisi (Lubisi et al., 2005).

113 Concerning ticks, the species, their geographical origin, their colony origin and status were reported. When ticks were
114 reared for less than five years in the laboratory, they were considered comparable to ticks sampled from the field due to
115 the limited number of generations occurring during this period. Some *Ornithodoros* ticks belong to species complexes and
116 soft tick systematics has greatly changed during the last decades. Tick species identification was updated in accordance
117 with the revision of valid tick names by Guglielmone (Guglielmone et al., 2010) and the mapping of their known distribution
118 (Vial, 2009). The more recent taxonomy study of southern African *Ornithodoros* ticks (Bakkes et al., 2018) could not be
119 used, due insufficiently precise location to attribute a species name among the *O. moubata* complex of species. Finally,
120 when determining tick geographical origin, 6 studies involving 4 different tick species (*O. coriaceaus, O. parkeri, O. moubata*,
121 and *O. porcinus*) did not report this information but since *O. parkeri* and *O. coriaceus* are known to be limited to North
122 America, especially the United-States (De La Fuente et al., 2008), they were assigned to this country.
123
124 Authors used various measurements to assess the tick vector competence for ASFV. Some authors reported numbers
125 of ticks positively detected with ASFV, while others scrutinized the virus titres in ticks or monitored ASFV kinetics in ticks
126 for several weeks or months, providing more comprehensive information on the virus persistence within its tick reservoir.
127 Some authors preferred to detect ASFV in tick transmission organs (salivary or coxal glands) or secretions (saliva or coxal
128 fluid). Such measurements suggest possible successful transmission to pigs although only transmission experiments can
129 confirm it. In these transmission experiments, clinical signs observed in pigs following tick bites confirm the ability of ticks
130 to transmit the disease. Detection of ASFV in pig blood is usually associated to confirm infection. Transmission between
131 ticks is either tested directly by measuring the proportion of transmitting ticks or the proportion of infected tick or indirectly
132 through the detection of ASFV in male reproductive organs (for sexual transmission) or female ovaries (for transovarial

133 transmission). However, this was not considered sufficient evidence to confirm such transmission pathways. Conversely,
134 the detection of ASFV in transmission secretions (e.g., saliva or coxal fluids) was considered sufficient evidence, as the virus
135 is already excreted in this case.
136
137 Based on these data, it was possible to evaluate three major components of the vector competence of the ticks: 1) the
138 tick infection (revealed by the crossing of the tick midgut by ASFV), 2) the ability of ticks to transmit ASFV to pigs (named
139 horizontal transmission) and 3) their ability to transmit ASFV to other ticks through sexual or transovarial vertical
140 transmission (named tick-to-tick transmission). Transmission to vertebrate hosts through tick bite or from ticks to ticks
141 cannot occur without the previous infection of the tick, which was thus considered as the main step to be assessed. In
142 addition, tick ability to transmit ASFV to pigs or other ticks are less frequently reported (N= 160 and N=54 over 900
143 experiments, respectively) likely because they are somewhat more difficult to assess than tick infection. Therefore, for each
144 experiment, we computed a binary variable, the infection status, according to any measurements providing direct
145 information on tick infection as well as indirect transmission measurements that imply previous tick infection (Figure 1).
146 More precisely, if ASFV transmission to pigs or ASFV transmission from ticks to other ticks were reported in papers, the
147 ticks were considered to be infected as the virus has necessarily crossed the tick organic barriers to reach transmission
148 organs and be transmitted.
149 If transmission failed or was not tested, the detection of ASFV in ticks was used as an indication of infection status.
150 Obviously when ASFV was not detected, ticks were considered as not infected. The only exception was when the detection
151 occurred on the same day as virus exposure, in which case no virus detection indicates a failure of experimental infection
152 or a too low detection threshold.



*Virus detection in the transmission organs is not a proof of transmission but the detection in the transmission fluids is a proof of transmission.
** we suspect in this case a failure in the experiment.

Figure 1 - Criteria used to determine the infection status of ticks after their virus exposure, with three classes (IS: Infection Status; DPE: Date post exposure; NA: Not Applicable, 1: Infected, and 0: Not Infected).

Different methods have been used by authors to detect ASFV in ticks, namely ASFV isolation/titration, observation of ASFV particles, and viral DNA or RNA detection using multiple designs of Polymerase Chain Reaction (PCR). In the included references, ASFV isolation/titration was based on haemadsorption (HAD), which is the ability of many ASFV strains to aggregate on red blood cells when they infect macrophages and create typical “rosettes” (Malmquist & Hay, 1960); this implies that the virus is able to replicate but does not necessarily confirm that it has crossed the midgut barrier. Similarly, detection of viral RNA also indicates active viral replication. Conversely the detection of viral DNA can be due to residual

164 virus from blood meal and does not mean that the virus is still active. However, we considered that those methods brought
165 equivalent results to assess infection status once the duration after exposure was taken into account.

166 Indeed, when ASFV was detected in ticks, a minimum duration of 61 days between tick exposure to ASFV and detection
167 of ASFV in tick (hereafter DPE for days post exposure) was chosen to distinguish successful viral replication inside the tick
168 from detection of residual virus after the infectious blood meal or virus inoculation. Indeed, the minimum duration for
169 blood meal digestion and clearance of ingested blood in soft ticks is approximately 4 weeks (Rowlands et al., 2009).
170 Furthermore, if tick infection is unsuccessful, ASFV can be detected during 4 weeks by isolation (Ribeiro *et al.*, 2015) and
171 after at least 49 days by qPCR (de Carvalho Ferreira et al., 2014; see also Bernard, 2015 for a review on ASFV kinetics inside
172 soft ticks). If tick infection is successful, virus generalization in ticks takes about 30 to 56 days (Plowright et al., 1970;
173 Kleiboeker et al., 1998; Basto et al., 2006; Burrage, 2013). Therefore, and as a precaution, if ASFV was tested and detected
174 before 61 DPE, the infection status was considered unknown unless virus was detected in organs other than the midgut. In
175 this case, this indicates that the virus has crossed the midgut barrier. Inoculation based on injection into the haemocoel
176 results in the virus being distributed throughout the tick. In this case, as the detection of virus in the organs was doubtful,
177 the infection status was recorded as unknown.

178 The experimental design used in the different studies was also reported, including: i) the exposure route for the tick
179 infection, ii) the ASFV titres in the inoculum used to infect the ticks (infectious dose), iii) the development stage of the ticks
180 tested in the study, iv) the DPE, v) the number of ticks tested in the study. Except for the DPE and the number of ticks
181 monitored, all parameters were categorized in different classes.

182 In field studies, viral titres in the hosts were not necessarily reported but they were considered to be high (>10^6
183 HAD_{50}/mL of blood) considering the viraemia usually observed in ASF diseased pigs (Plowright et al., 1968). Tick stage was
184 classified as early from larva to nymph 3 and as late from nymph 4 to adult.

185

186 *Statistical analysis of the tick infection status*

187 A statistical analysis was carried out to identify factors potentially affecting the tick infection status. More precisely, we
188 investigated if factors related to the nature of tick-virus association or the experimental design influenced the infectious
189 status (see above for details) of the ticks in published experimental trials. The explanatory variables were: the ASFV strain
190 and genotype, the tick species, the potential geographical co-occurrence of tick and virus as an indication of possible tick-
191 virus adaptation (ASFV and ticks from the same country versus from different countries), the viral titre in infectious blood
192 meal and the exposure route for tick infection, the tick stage, the tick colony status and the host from which the ASFV strain
193 was sampled. Using a dataset where all ticks were adults, we also tested the influence of tick sex on infectious status (along
194 with all other factors except tick stage). All statistical analyses were performed on R 4.2.2 (R Core Team, 2022). To assess
195 which factors influenced the infection status, we applied a generalized mixed model with a binomial family. The tick species,
196 virus genotype and virus strain were set as random effects to account for the fact that only a random fraction of soft tick
197 species and virus genotypes and strains were sampled. All other factors were set as fixed effects. The significance of random
198 effects was tested using a likelihood ratio test (Zuur et al., 2009). We then selected the best parsimonious models (with the
199 remaining 6 fixed effects) based on the AIC (Akaïke Information Criterion). In this best model, the significance of fixed effects
200 was tested using Chi^2 tests between models and post-hoc tests, with Tukey HSD correction, were performed.

201

202 *Assessment of the overall tick vector competence for ASFV*

203 Although our main assumption is that vector competence results are influenced by the experimental design, we
204 attempted to assess the overall vector competence of the various *Ornithodoros* tick-ASFV associations. Based on the three
205 main components described above, we scored each tick-ASFV association, according to the following ranking: “score 0” for
206 ticks that were unable to become infected or for which it was impossible to conclude (see flow chart figure 2) ; “score 1”
207 when ASFV was able to cross tick midgut and replicate in ticks; “score 2” when transmission from tick to pig was successful
208 ; and, “score 3” for ticks validating all components of vector competence, including ASFV transmission from ticks to other
209 ticks. The attribution of a score was based on all data available from the different included references related to the
210 considered tick-ASFV association, and thus the longest period of monitoring and the best vector competence performance
211 for this association.

212

213 Attributing graduate scores of vector competence sounds as if that associated transmission events are also graduate.
214 This is not the case: even if horizontal transmission scored 2 and sexual or transovarial transmissions scored 3, the success
215 of tick-to-tick transmission does not necessarily imply the efficiency of horizontal transmission. For example, *O. erraticus*
216 showed vertical transmission with the viral strain OURT88/1 but no transmission to pig (Pereira de Oliveira et al., 2019;
217 Pereira De Oliveira et al., 2020).

218

Results

Bibliometric description

The initial bibliographic search generated 236 references using Scopus and 138 by Pubmed, with 2 articles detected only by Pubmed. The ETHOS database of thesis manuscripts and our manual bibliography search allowed identifying 8 more resources. Among the final 246 references selected, 75 were reviews, 163 scientific papers and 8 thesis manuscripts. In this pool of bibliographic references, 39 references presenting vector competence original results were included in the final dataset. They consisted of 5 field studies monitoring natural tick infections, 34 articles of laboratory experiments on ticks and 2 mixed papers (Table 1). As shown in figure 2, the number of publications pertaining to the vector competence of *Ornithodoros* ticks for ASFV was consistently low over the years, while the total number of references related to ticks and ASFV progressively increased from the 1980s to 2022.

Thirty-nine authors were reported as first and/or last authors of the selected publications and were considered as "experts". Their period of expertise, including all their publications on ASFV & ticks, varied from 1 to 34 years. After 2015, 9 out of 39 experts continued to publish in this domain and can be considered the current core of experts on the vector competence of ticks for ASFV.

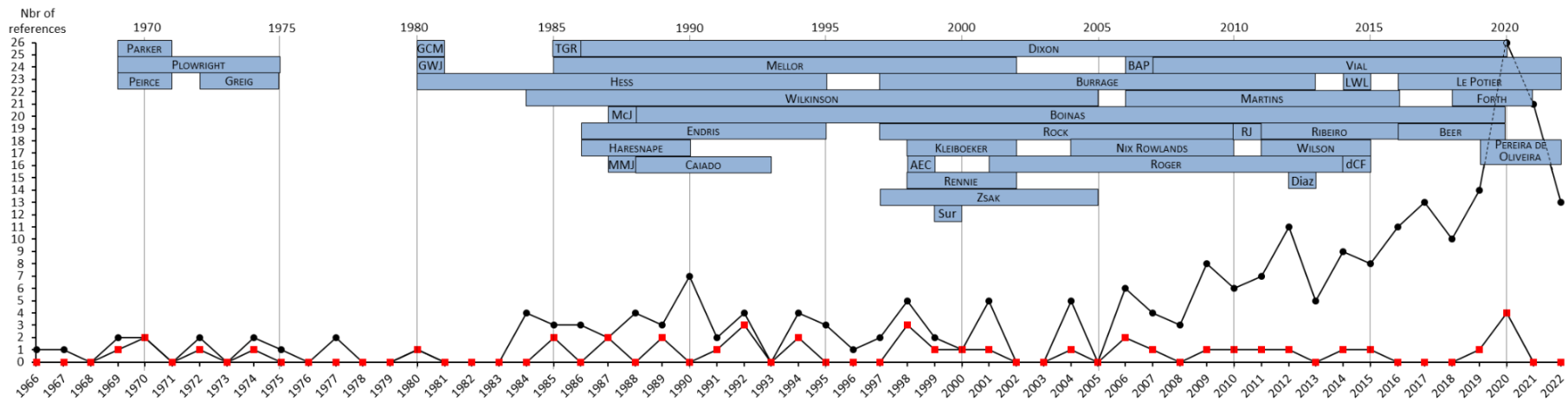


Figure 2 - Number of bibliographic references published each year, from 1966 to 2022, on "African swine fever" AND "tick" (black dots = 246 screening references) and on the vector competence of *Ornithodoros* ticks for ASFV (red dots = 39 included references). The names of first and last authors of the 39 included references were reported in blue boxes at the top of the graphic. The length of boxes indicates their respective period of expertise, during which they published in the "African swine fever" AND "tick" fields (i.e., among the 246 screening references). List of the abbreviation author name: AEC: Anderson E.C.; BAP: Basto A.P.; dCF: de Carvalho Ferreira H.C.; GWJ: Gladney W.J.; GCM: Groocock C.M.; LWL: Loeffen W.L.; McJ: McCoy J.P.; MMJ: Monahan M.J.; RJ: Ravaomanana J.; TGR: Thomson G.R.

Data related to the biological material: ticks and ASFV

A database was created to record all the extracted data. Each record comprises a precise combination of any modalities of informed indicators concerning the publication, the ticks, the ASFV strain and the experimental design. From the 39 included references, 2036 records corresponding to 900 unique experiments were extracted. For some references, authors detailed the results of their experiment for each tick or with multiple records over time for the same ticks. Each experiment was characterized by a combination of tick species, virus strain and experimental conditions (see Annexes 2 and 3). In total, the tick species and ASFV strains represented 51 tick-virus associations and more than half (34/51) appeared in only one publication.

For the ticks, ten species were tested for their vector competence for ASFV. The Iberian tick *O. erraticus* was the most studied (representing 44% of the reported experiments), followed by the *O. moubata* complex of species, including *O. porcinus* and *O. moubata* sensu stricto (43%). The North American *O. coriaceus* (6.4%) were third, then they were far followed by the other species *O. puertoricensis, O. verrucosus, O. savignyi, O. parkeri, O. sonrai, O. turicata* (3.7% - 1.0% - 0.8% - 0.4% - 0.4% - 0.2 % respectively). The geographical origins of ticks specified in the included references are presented in figure 3. All *O. erraticus* ticks tested came from Portugal, and most of them from the same region of Alentejo, while *O. moubata* and *O. porcinus* ticks came from diverse countries, which is representative of their large distribution range in East and Southern Africa.

A total of 38 different ASFV strains were tested. Most ASFV strains used in the studies were isolated from ticks and pigs (43.1% and 40.4% of the reported experiments, respectively). Only four strains studied in 16.2% of the experiments were isolated from warthogs and 0.2% of virus strains are from undetermined hosts. ASFV strains were geographically distributed over 17 different countries, mostly in Africa, and belonged to 8 genotypes over the 23 genotypes described so far, with a large representation of the genotype I (64.9% Figure 3). The genotype of the 114a and Transvaal CV strains from South Africa remains unknown.

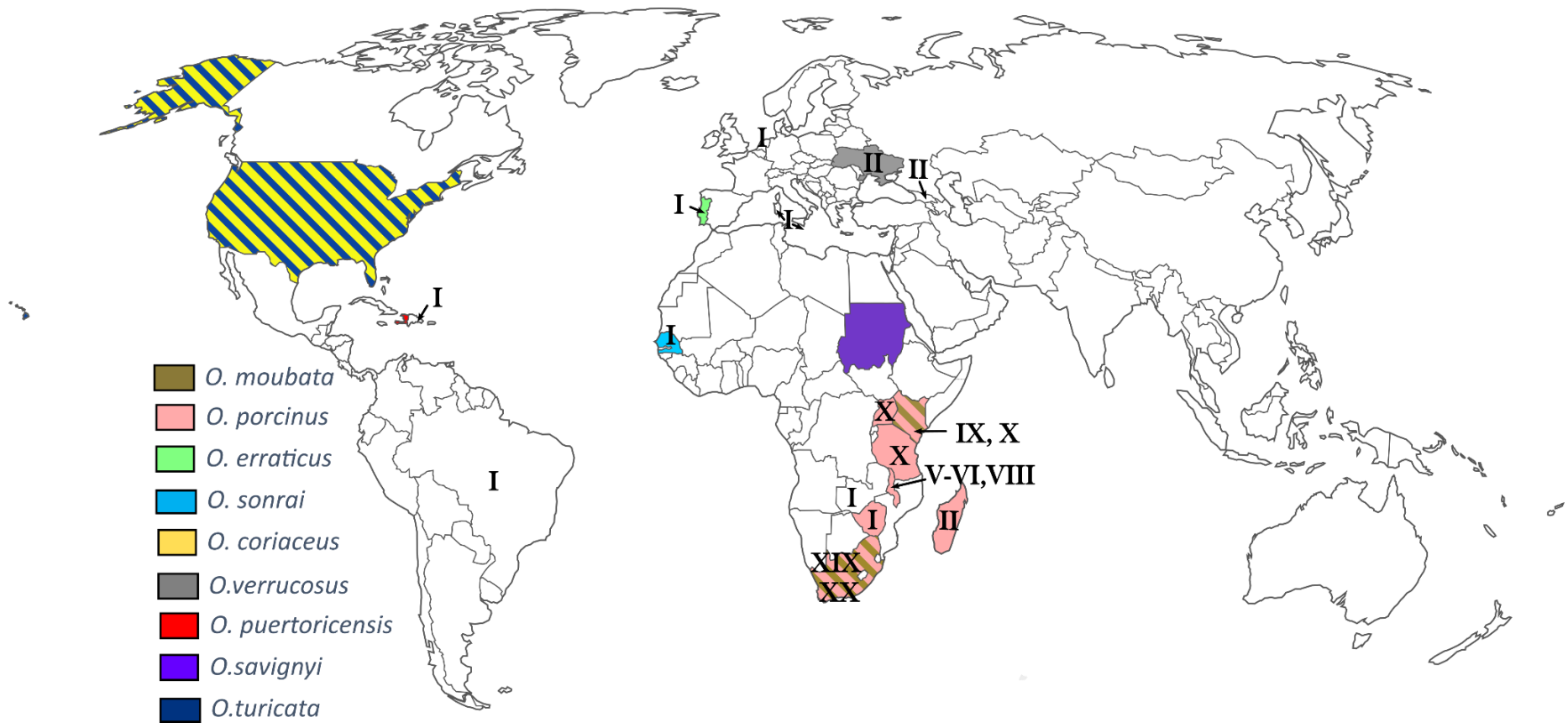


Figure 2 - Countries of origin of *Ornithodoros* tick species (coloured according to the species) and ASFV genotypes (indicated by genotype number associated with each country), involved in tick-ASFV associations studied in included references. The origin of the tick *O. parkeri* was not indicated but should be the United-States, as described in the literature.

Data related to the experimental design

Of the 900 experiments recorded, half used ticks directly sampled from the field (especially *O. erraticus* and *O. porcinus*) or reared in insectary for less than 5 years (48.7%). The other experiments used ticks reared in the laboratory for more than 5 years with some reared until 25 years for one study on *O. turicata* (47.2%). It was not possible to find information for the remaining experiments. The majority of experiments (57.9%) involved ticks in their later developmental stages, ranging from nymph 4 to adults. Early stages, from larva to nymph 3, were employed in 23.3% of the experiments. In the remaining

experiments, authors either utilized a combination of early and late stages (14.7%) or did not provide information about the specific developmental stage used (4.1%). The number of ticks tested for each experiment was fairly low especially in laboratory experiments (median=7 ticks tested, mean=30.03, range=[1;1141]).

Four methods were used to perform viral ASF inoculation to the ticks. Natural blood feeding on vertebrate hosts was reported either in field studies, or in some laboratory experiments using experimentally infected pigs. This method represented almost half of the total experiments conducted (47.4%). Two artificial feeding methods are reported: the longest established method uses capillary tubes inserted on tick mouthparts (8.8%) while a more recent approach uses animal skin, parafilm, or silicone membranes (35.7%). Another artificial infection route was the syringe inoculation of ASFV directly in the tick haemocoel (8.1%). ASFV infectious dose used to infect ticks was very heterogeneous and thus classified in three categories. Most experiments (78,4%) used medium to high viral doses (between 10^4 and 10^6 or over10^6 HAD_{50}/mL of blood). The DPE was very variable, ranging from 0 day (presumably used as a control for successful viral exposure) to up to 8 years (median value=58.0 days and mean value = 115.5 days), meaning that half experiments reported a DPE lower than the duration required to differentiate a successful viral replication inside the tick from a detection of residual virus after the infection.

Factors influencing the likelihood of tick infection

On the initially 900 recorded experiments, we obtained a dataset of 407 observations with full information regarding tick infection status and experimental conditions (Annexes 4 and 5). Among the random effects tested, the tick species and virus genotype had no effect on the infection status but the viral strain had (χ_1^2=4.879 p-value= 0.027). Model selection based on AIC ended up with three variables displaying large and comparable importance across all models: virus titre, tick

stage and tick colony status (Figure 4 left). All those three variables had significant effects on infectious status (Figure 4 right).

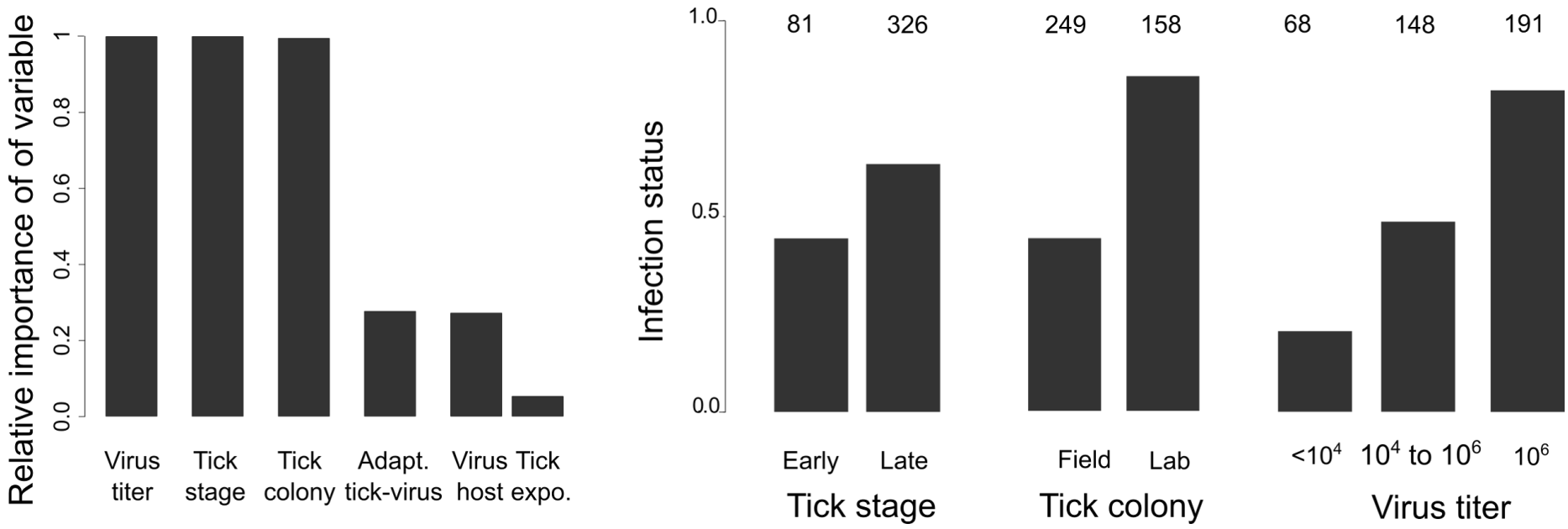


Figure 4 - *Left*: Relative importance of explanatory variables across all models explaining infection status. The importance value for a particular variable is equal to the sum of the weights for the models in which the variable appears. *Right*: Effect of tick stage, tick colony and virus titre on the infection status (all three effects are significant). Mean of infection status (i.e., proportion of experiments where ticks were infected). Values above the bars are the number of experiments in each level. Virus titre in HAD_{50}/mL of blood.

In more details, a higher viral titre corresponded to a higher likelihood of tick infection (χ^2_2= 38.493, p-value=4.423×10^{-9}). Bigger nymphs and adults were more prone to get infected than small nymphs (χ^2_1=17.880, p-value=2.353×10^{-5}). And ticks from laboratory colonies had higher probability of infection than ticks recently sampled in the field (χ^2_1= 14.031, p-value=1.798×10^{-4}). The potential geographical co-occurrence of tick and virus, the exposure route for tick infection and the virus host were not significantly linked with infection status even if they were present in some of the best models (Annex 6). Using the dataset containing only experiments with adult ticks showed that sex had no influence on infection status.

Vector competence scores for ASFV

Figure 5 summarizes the vector competence score for each of the 51 associations between soft ticks and ASFV virus tested so far. In more detail, 23.5% of the tick-ASFV associations presented a vector competence score null (score 0) i.e., ticks were unable to become infected or it was impossible to conclude on their infection status. For 27.5% of tick-ASFV associations, only tick infection (score 1) was achieved. Transmission from ticks to pigs was tested in 64.7% of tick-ASFV associations and was successful in 29.4% (score 2). Finally, 33.3% of tick-ASFV associations were assessed for ASFV transmission from ticks to ticks and 19.6% succeeded to transmit (score 3).

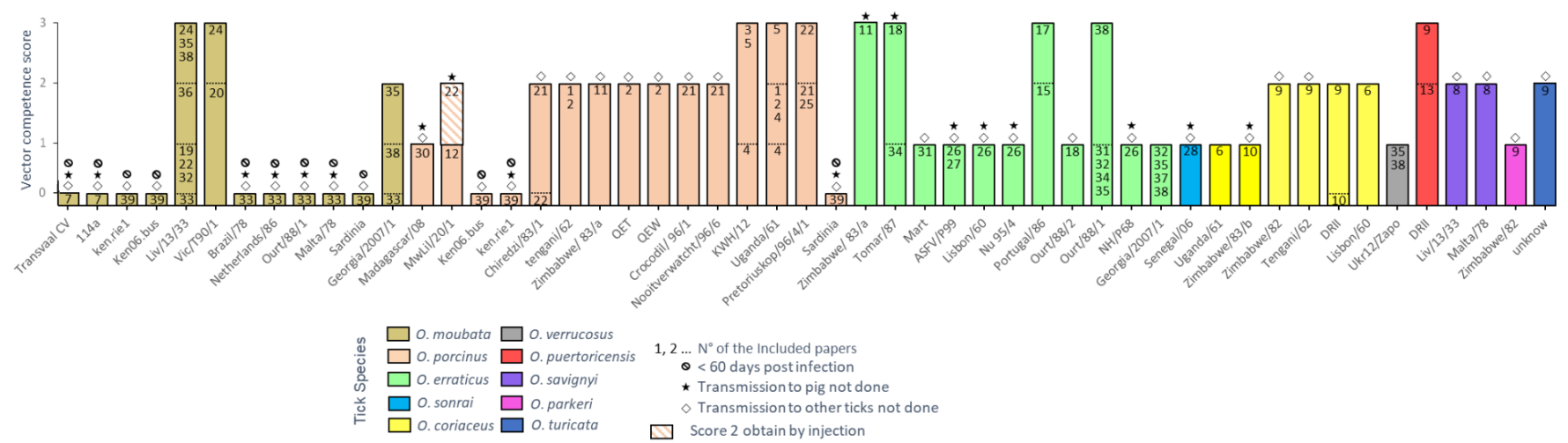


Figure 5 - ASFV vector competence scores for the different tick-ASFV associations studied in the included references (score 0: no tick infection or no information to conclude, score 1: successful tick infection, score 2: successful ASFV transmission to pigs, score 3: successful ASFV transmission to other ticks). In each histogram bar, the numbers are related to the included references recorded in Table 1. For each included reference, an individual score is given according to available results in this paper. The overall vector competence score for a given tick-virus association is the best vector competence result reported from all included references related to this tick-ASFV association.

323

324 Only 27.5 % of tick-ASFV associations were fully tested for vector competence (including tick infection, transmission to
325 pig, and transmission to other ticks) and 15.7% were fully competent, meaning that they reached scores 1, 2 and 3.
326 Conversely, 3 associations reached score 3, without being tested for horizontal transmission (O. *erraticus*-Zimbabwe/83/a
327 and O. *erraticus*-Tomar/87) or by failing to transmit to pigs when tested (O. *erraticus*-Ourt/88/1). In one tick-ASFV
328 association (*O. porcinus*- MwL1/20/1) transmission capacity was suggested by virus secretion in saliva and in coxal fluid only
329 via virus direct injection into tick hemolymph.

330 At the species level, when considering only scores 1 and 2, most tick species tested were confirmed to be competent
331 vectors for at least one ASFV strain. This competence remains unclear for 3 species that were either tested with only one
332 ASFV strain and failed to transmit the virus to pig and/or to ticks (*O. parkeri* and *O. verrucosus*) or never tested for
333 transmission *(O. sonrai)*. Regarding ASFV transmission to other ticks, 6 tick species were tested and 4 (*O. moubata*, *O.*
334 *porcinus, O. puertoricensis*. and *O. erraticus)* succeeded for at least one ASFV strain whereas 2 (*O. coriaceus* and *O.*
335 *verrucosus)* that were tested with respectively three and one ASFV strains, failed. Finally, high heterogeneity of vector
336 competence scores was observed within a same tick species depending on ASFV strains used (e.g. score 3 for *O. moubata*-
337 LIV13/33 and score 0 for *O. moubata*-Brazil/78), and sometimes for a same tick-ASFV association (e.g. scores 0/1 and 2 for
338 two *O. turicata* colonies of different ages with the same ASFV strain).

339

Discussion

Bibliographic resources

This paper is the first exhaustive review of all the original studies published on the vector competence of soft ticks for ASFV until 2023. Despite an exhaustive screening of bibliographic resources, only 39 references were considered and the expert panel had always been limited, as exemplified by only 9 publishing experts since 2015. This relative paucity of bibliographic resources regarding soft tick competence for ASFV may be attributed to the difficulty of investigating their vector competence, both in laboratory and in field conditions. Indeed, sampling endophilous *Ornithodoros* ticks and developing relevant methods to detect ASFV in natural tick populations (Jori et al., 2013; Oura et al., 2013) or rearing soft ticks and amplifying ASFV in laboratory conditions are long and laborious tasks (Vial, 2009; Carrascosa et al., 2011). In addition, although ASF is of high veterinary and economic concern, vectorial transmission is seen as occasional with a relatively minor role in disease spread at least in some regions (Guinat et al., 2016). Nevertheless, soft ticks play a key role in the maintenance of the virus and this is why characterizing competence for tick-virus associations is required to assess the risk of ASFV introduction and spillover as Golnar *et al.* (2019) did for the US.

Vector competence and tick-virus co-adaptation

Although all references included in this study aimed to evaluate the vector competence of soft ticks for ASFV, we noticed a considerable diversity of vector competence measurements that yield distinct information. As a consequence, vector competence was only partially assessed for most tick-ASFV associations, with a noticeable decrease of studies along the successive biological steps of vector competence, from the tick infection to ASFV transmission by tick to pigs, and then by

359 tick to other ticks. In addition, more than half of tick-ASFV associations were characterized by only one single article.
360 Heterogeneous vector competence scores were observed within species between viral strains. For instance, *O. moubata*
361 showed efficient vector competence for only 3 viral strains out of the 12 tested thus far. This could be interpreted either as
362 a lack of sufficient reliable studies or high tick-virus specificity. This latest hypothesis is in agreement with our results
363 showing a significant effect of viral strain on tick infection status.

364 Adaptation between arthropod vectors and viruses is based on genetic features defining susceptibility in both organisms
365 and the selection of susceptibility may be mediated partly by detrimental effects of arboviruses on vector physiology
366 (Gillespie et al., 2004). In soft tick-ASFV model, the presence of ASFV MGF360 genes, the lectin-like EP153R gene, or the
367 CD2-like EP402R gene enhance the entry and the replication of ASFV into ticks (Burrage et al., 2004; Rowlands et al., 2009).
368 Leaving their original sylvatic cycle involving warthogs and ticks, some ASFV strains naturally lost these genes through long-
369 term circulation among Iberian domestic pigs, or by multiple passages on pig macrophages for vaccine production (Portugal
370 et al., 2015). Concerning these vector susceptibility genes, some of them, such as MGF 360, are involved in the suppression
371 of the immune response of vertebrate and arthropod hosts against ASFV (Portugal et al., 2015). In addition, arthropods are
372 known to display RNA interference as an important immune response against virus infection (Vijayendran et al., 2013). The
373 involvement of such molecular pathway has recently been suggested in soft ticks with ASFV- like integrated elements coding
374 for small interfering RNA in *O. moubata* (Forth et al., 2020). More specifically, it appears that a greater number of these
375 small matched with ASFV genomes from genotype II than with genotype I, contributing to the variation in vector
376 competence between viral strains.

377 We can suppose that field ticks, co-evolving or not with ASFV, may develop a much more heterogeneous and adaptive
378 response against ASFV infection and show a lower success of infection, as it was already shown in some mosquito-virus

379 models (Gillespie et al., 2004). Indeed, some authors previously reported very low ASFV infection rates in field ticks
380 (Plowright et al., 1969; Haresnape & Wilkinson, 1989; Boinas et al., 2011), as well as over-mortality in laboratory ASFV
381 highly infected ticks (Endris & Hess, 1994; Kleiboeker & Scoles, 2001). In our study, laboratory tick colonies reared for more
382 than five years were shown to be significantly much more infected by ASFV than field ticks or recently established laboratory
383 ticks. In addition, ticks from old laboratory colonies may be more prone to efficient artificial blood feeding, increasing the
384 blood volume and ASF virus intake.

385 Despite heterogeneous vector competence according to studies and viral strain tested, experimental evidence shows
386 that 7 *Ornithodoros* species from Africa (*O. moubata, O. porcinus and O. savignyi*), Europe (*O. erraticus*) and North America
387 (*O. coriaceus, O. turicata and O. puertoricensis*) can be infected by at least one strain of ASFV and then transmit it to pigs.

388

389 *Effect of experimental factors on tick competence*

390 Our analysis of vector competence references demonstrated the importance of the experimental design on vector
391 competence results. Several factors related to the choices of biological material and methodologies were tested. The ASFV
392 titre in the inoculum for infecting ticks appears as a key parameter in the vectorial competence experiments, with likelihood
393 of tick infection above 50% when ASFV load was higher than 10^6 HAD_{50}/mL. Accordingly, a threshold of $10^{5.75}$ HAD_{50}/mL was
394 previously determined by Ribeiro (Ribeiro et al., 2015) for the specific ability of *O. erraticus* to maintain and multiply two
395 Portuguese ASFV strains. Forth *et al.* (2020) also demonstrated an impact of ASFV titre on tick infection probability and
396 load. Soon after ingestion, ASFV has to cross the tick midgut barrier to be amplified in replication units localized in tick
397 endothelial cells and then enter the tick hemolymph (Burrage, 2013). These results may suggest that the tick midgut and
398 other tick membranes act as porous surfaces; the probability of ASFV entry would thus depend on the number of available

399 pores and on the virus load (Franz et al., 2015). Tick immune system such as RNAi could also block low level of ASFV infection
400 (Forth et al., 2020).

401 The development stage of ticks had a significant impact on tick infection status, with better results for late stages (from
402 nymph 4 to adults). This pattern confirms previous results on *O. erraticus*-Tomar and *O. erraticus*-OURT88/1 from Ribeiro
403 (Ribeiro et al., 2015). This was explained by higher blood volume intake for late and large stages, and therefore highest
404 ASFV titre inside the tick after blood meal digestion. In addition, even if female take a larger blood meal than males, we
405 found no effect of observed sexual dimorphism in adults on the likelihood of tick infection which is in agreement with
406 Ribeiro *et al.* (2015). In this study, the authors suggest that, in adults, the number of ASFV particles already reached a certain
407 threshold necessary to cause tick infection.

408 The route for tick infection was expected to play a role on tick competence. Natural feeding on viraemic pigs may provide
409 higher viral titre (usually $>10^6$ HAD_{50}/mL) than artificial feeding on membrane or with capillary (from 10^4-10^6 HAD_{50}/mL)
410 due to the difficulty for amplifying ASFV on pig macrophages. The injection of the virus into the haemocoel results in the
411 dissemination of the virus throughout the tick body, which is a traumatic process for the tick (Bonnet & Liu, 2012). Despite
412 differences between inoculation methods, this does not seem to translate into any significant differences on the success
413 rate of infection in our dataset. This could be attributed to our dataset being incomplete and imbalanced, with the virus
414 titre being a confounding factor. The impact of inoculation methods could be specifically addressed by conducting
415 dedicated studies comparing the various methods with a similar virus titre. Similarly, we did not find any effect of the initial
416 host in which viral strain was isolated on tick competence.

417 Our review highlighted the huge diversity of measurements used in the included references. They differ in their value
418 for informing the various steps of tick competence. Apart from PCR based viral detection, all the other methods reported

419 from included references show some weakness to assess tick infection. For instance, ASFV isolation and titration on pig
420 alveolar macrophages was largely used by authors but this technique may suffer from inhibition issues due to cytotoxic
421 effect of tick components on pig macrophages and its achievement in at least 6 days is very time-consuming (Oura et al.,
422 2013). In our analysis, the main issue was to differentiate "residual" infection that consisted of remaining virus or viral DNA
423 in the tick midgut before complete digestion, from "true" infection where active virus crossed the tick midgut barrier and
424 began its replication in tick cells. Accordingly, we recommend that viral DNA detection should not be used until 2 months
425 after inoculation. Alternatively, Reverse Transcription quantitative PCR could be used with a shorter time frame, as it
426 detects ASFV gene duplication and expression, indicating ASFV crossing of the tick midgut barrier where replication units
427 are located. Finally, favoring oral inoculation of the virus, instead of virus injection to the hemolymph, would avoid doubtful
428 detection of ASFV and bypass of the immune system avoiding a counterfeit infection (*O. porcinus*-MwLil/20/1). Since viral
429 titre has the largest effect on tick infection success, preferring blood from viraemic pigs would insure sufficient virus load
430 and probably an ideal virus hemadsorption to erythrocytes. Similarly, when feasible, late nymphs or adult ticks should be
431 used since they will allow large blood intake.
432
433

434 **Conclusion and perspectives**

435 The examination of 39 references on the vector competence of *Ornithodoros* soft ticks for ASFV highlighted factors
436 influencing vector competence results. For the same tick-ASF association, vector competence results may vary according
437 to the methodology used for infecting ticks (ASFV titre in the inoculum), the choice of biological material (viral strain, tick

438 development stage of tick, tick colony), and the techniques used to monitor and assess the likelihood of tick infection.
439 Although comparisons were difficult due to the scarcity of complete vector competence assessment for many tick-ASFV
440 associations, our analysis highlighted some standards that could be used for further investigations on the vector
441 competence of *Ornithodoros* ticks for ASFV.
442

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Author contributions

JB coordinated the study, collected all bibliographic resources, extracted the data and wrote the manuscript. HJ-P analysed the data and wrote the manuscript. SM and JO analysed the data. LV and M-FLP coordinated the study and wrote the manuscript.

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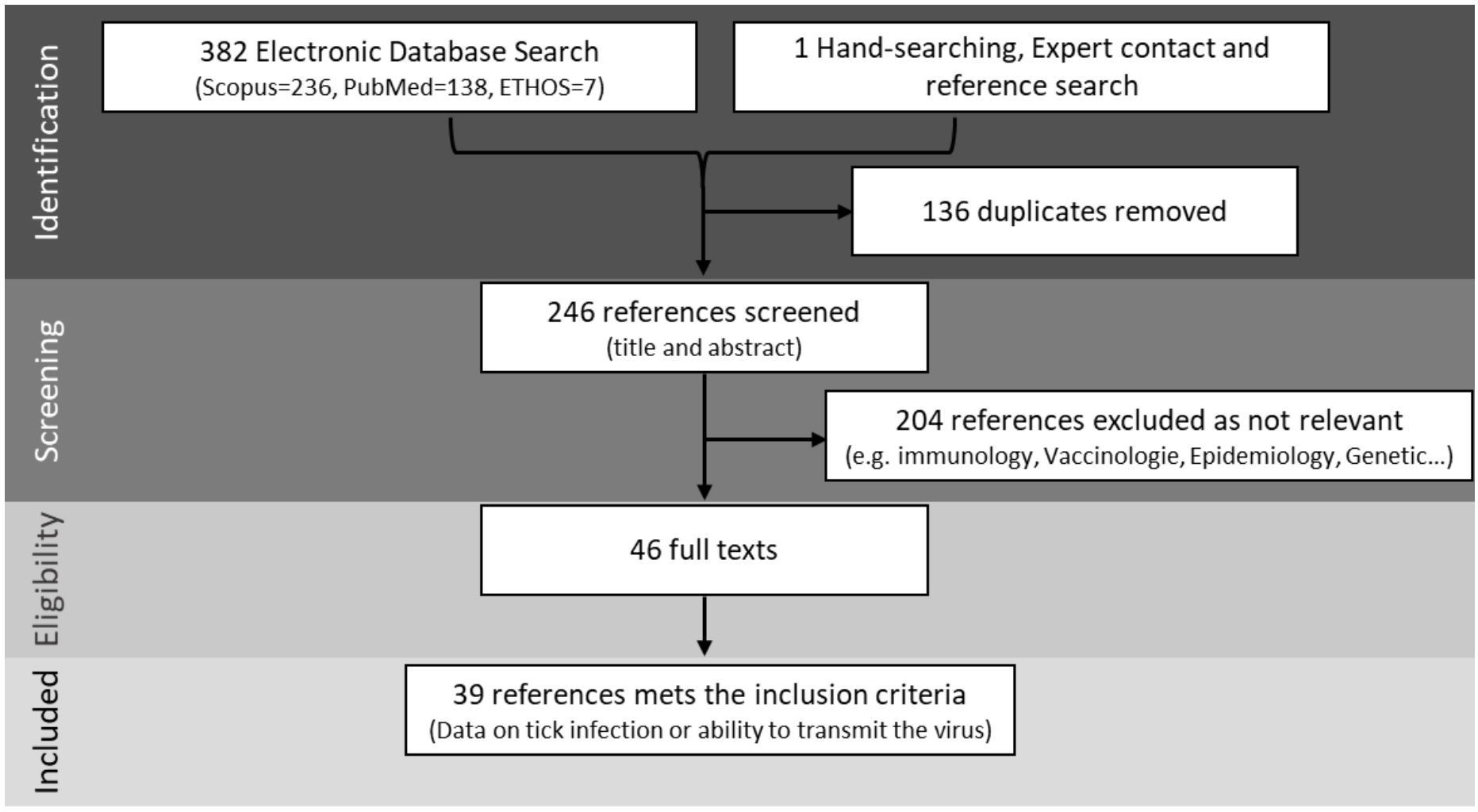
Data, scripts and codes availability

All data presented here and the script used for statistical analyses are available https://doi.org/10.18167/DVN1/RYLTJ7.

Appendix



Annex 1: Article selection process according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines

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572 Annex 2: Number of experiments reported for each virus strain, virus genotype and tick species in the whole dataset (900 experiments)

Virus strain		Virus genotype		Tick species	
asfvp99	30			coriaceus	58
brazil78	4			erraticus	396
chiredzi831	38			moubata	107
dr2	56			parkeri	4
lisbon60	10			porcinus	279
liv1333	46			puertoricensis	33
malta78	9			savignyi	8
mart	5			sonrai	4
netherlands86	4			turicata	2
nhp68	30			verrucosus	9
nu954	5	I	584		
ourt881	110				
ourt882	40				
portugal86	51				
sardinia	10				
senegal06	4				
tomar87	93				
vict901	4				
zimbabwe82	7				
zimbabwe83a	17				
zimbabwe83b	11				
georgia20071	42	II	52		
madagascar08	1				
ukr12zapo	9				
tengani62	19	V	19		
mwLil201	22	VIII	22		
kenrie1	20	IX	10		
ken06bus	10	X	176		
kwh12	30				
qet	12				
qew	17				
uganda61	97				
crocodil961	4	XIX	8		
nooitverwatcht966	4				
pretoriuskop9641	19	XX	19		
114a2	1	unknown	10		
Otu87	2				
transvaalcv	7				

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Annex 3: Number of experiments reported in each category of the studied experimental factors in the whole dataset (900 experiments). NA: not available.

Exposure route		Tick stage		Tick colony		Virus host		Viral titer		Geographic co-occurrence	
artificial	319	early	210	field	438	pig	364	$<10^4$	109	yes	747
capillary	79	late	522	lab	425	tick	389	10^4 to 10^6	296	no	153
natural	427	mix	131	NA's	37	warthog	145	$>10^6$	495		
inoculation	75	NA's	37			NA's	2				

Annex 4: Number of experiments reported for each virus strain, virus genotype and tick species in the dataset analysed (407 experiments).

Virus strain		Virus genotype		Tick species	
asfvp99	20			coriaceus	2
chiredzi831	16			erraticus	244
dr2	3			moubata	44
lisbon60	2			parkeri	1
liv1333	29			porcinus	103
malta78	1			puertoricensis	3
nhp68	26			savignyi	4
nu954	5			verrucosus	6
ourt881	61	I	291		
ourt882	21				
portugal86	25				
sardinia	4				
tomar87	69				
vict901	4				
zimbabwe82	1				
zimbabwe83a	2				
zimbabwe83b	2				
georgia20071	20	II	26		
ukr12zapo	6				
tengani62	6	V	6		
mwLil201	6	VIII	6		
kenrie1	4	IX	5		
ken06bus	5				
kwh12	20				
qet	7	X	72		
qew	8				
uganda61	33				
pretoriuskop9641	1	XX	1		

Annex 5: Number of experiments reported in each category of the studied experimental factors in the dataset analysed (407 experiments).

Exposure route		Tick stage		Tick colony		Virus host		Viral titer		Geographic co-occurrence	
artificial	169	early	81	field	249	pig	172	$<10^4$	68	yes	369
capillary	46	late	326	lab	158	tick	174	10^4 to 10^6	148	no	38
natural	154					warthog	61	$>10^6$	191		
inoculation	38										

Annex 6: Five best models with the included variables influencing infection status (note that all models have «virus strain» as random effect), corrected Akaike Information Criteria and weight of the model (probability that the model is the best out of all models considered).

Adaptation tick/virus	Exposure	Colony type	Tick stage	Viral titer	Viral host	AICc	delta	weight
		+	+	+		393.6	0.00	0.506
+		+	+	+		395.6	2.01	0.185
		+	+	+	+	395.7	2.07	0.180
+		+	+	+	+	397.4	3.84	0.074
	+	+	+	+		399.6	5.97	0.026