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**Avian blood parasite richness decreases with MHC class I
loci number**

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This article does not present research with ethical considerations

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Data

It is a condition of publication that data, code and materials supporting your paper are made publicly available. Does your paper present new data?:

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All data used in the analysis is available in Table S1 and S2.

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O.V. & C.L. wrote the manuscript. O.V. performed the comparative analysis. C.L. and M.G. designed the analysis. All authors critically revised the manuscript, gave final approval for its publication and agree to be held accountable for the work performed therein.

1 **Avian blood parasite richness decreases with MHC class I loci number**

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3

4

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19

20 **Abstract**

21 Major Histocompatibility Complex (MHC) genes are among the most polymorphic in the
22 vertebrate genome. The high allele diversity is believed to be maintained primarily by
23 sexual and pathogen-mediated balancing selection. The number of MHC loci also varies
24 greatly across vertebrates, most notably across birds. MHC proteins play key roles in
25 presenting antigens on the cell surface for recognition by T cells, with class I proteins

26 specifically targeting intracellular pathogens. Here we explore the hypothesis that MHC
27 class I diversity (measured as loci number) co-evolves with haemosporidian parasite burden
28 of the host. Using data on 54 bird species we demonstrate that high MHC class I diversity is
29 associated with significantly lower richness of *Plasmodium*, *Haemoproteus* as well as
30 overall haemosporidian parasite lineages, the former thus indicating a more efficient
31 protection against intracellular pathogens. Nonetheless, the latter associations were only
32 detected when MHC diversity was assessed using cloning and not 454 pyrosequencing-
33 based studies, nor across all genotyping methods combined. Our results indicate that high
34 MHC class I diversity might play a key role in providing qualitative resistance against
35 diverse haemosporidian parasites in birds, but further clarification is needed for the origin
36 of contrasting results when using different genotyping methods for MHC loci
37 quantification.

38

39 **Keywords**

40 Haemosporidians, copy number variation, parasite richness, pathogen-mediated selection,
41 comparative analyses, MHC diversity

42

43 **1. Introduction**

44 The Major Histocompatibility Complex (MHC) is known to be the most variable gene
45 group in vertebrates, both in terms of allelic diversity and gene number [1]. MHC genes
46 code for cell surface glycoproteins that bind to antigenic peptides and present them to cells
47 of the immune system, initiating adaptive immune responses. Proteins encoded by the
48 MHC genes ensure the immune presentation of a broad spectrum of peptides, both derived
49 from the intracellular (class I proteins) or extracellular (class II proteins) space [2]. High
50 MHC diversity, reflected by high allele diversity or loci number, is often related to the

51 ability to present a wider repertoire of antigens to the immune system, thus representing a
52 genetic marker of disease resistance [3] but see [4]. Several, mutually non-exclusive
53 hypotheses have been put forward to explain the maintenance of high MHC diversity, such
54 as the heterozygote advantage (i.e., MHC diversity conferring disease resistance), negative
55 frequency-dependent selection (benefit of rare MHC alleles in pathogen detection) or
56 fluctuating selection (spatial or temporal change in the selective advantage of MHC alleles)
57 [5,6].

58

59 The number of MHC loci varies greatly across vertebrates, being the result of a complex
60 evolutionary history, involving gene duplications and translocations [7,8]. For example,
61 species from the Galliformes order possess only two MHC class I genes [9,10], which is
62 considerably lower than in other bird lineages [11,12], such as passerines. Several studies
63 reported that a low number of MHC loci could represent the ancestral state in birds, and
64 that the highest diversification in copy numbers occurred relatively late in the avian
65 radiation, reaching its highest diversity in passerines [12]. While, parasite-mediated
66 selection has been considered as the most prominent component driving MHC
67 diversification [13], it is now widely accepted that in addition to the pathogen burden,
68 sexual selection and risk of developing autoimmune diseases or immunopathologies may
69 together shape the evolution of an optimal rather than maximal MHC diversity [3,4,13–15].

70

71 Malaria and closely related haemosporidian parasites are intensively investigated vector-
72 borne parasites in birds, partly because of the high diversity of hosts they are able to infect,
73 and their nearly worldwide distribution [16]. A series of experimental studies [17–21], have
74 demonstrated the substantial costs associated with haemosporidian infection, in terms of

75 reproductive success, health condition and survival. Hence, immunological adaptations
76 targeting and eliminating such infections can provide considerable fitness benefits. Key
77 components of these defenses are the MHC proteins. Nonetheless, knowledge on the co-
78 evolution of MHC diversity and avian haemosporidian parasite burden across species
79 remains limited [22–26]. However, other host-parasite systems found strong evidences that
80 specific MHC alleles confer resistance to pathogens [27,28].

81

82 With the increasing use of molecular tools, a large number of bird species have been
83 recently screened for haemosporidian parasites. The MalAvi database represents a unified
84 database compiling these data, covering genetic and geographical data of avian blood
85 parasites (*Plasmodium*, *Haemoproteus*, *Leucocytozoon* genera). It currently encompasses
86 more than 14,400 records with 4,520 lineages detected in more than 2,100 host species
87 [29]. Taking advantage of this unique database, here we explore whether MHC diversity
88 co-evolves with haemosporidian lineages richness. Given that haemosporidian parasites are
89 obligate intracellular parasites, here we focus on the MHC class I genes, exploring
90 relationships between gene copy numbers (hereafter MHC-I diversity) and blood parasite
91 lineages richness. Based on earlier species-specific studies on the link between MHC-I
92 allelic diversity and blood parasites [23,26] and according to the heterozygote advantage
93 hypothesis, we predict a negative association between MHC-I diversity and the diversity of
94 intracellular parasites across host species. Nonetheless, an opposite association can also be
95 predicted since studies focusing on extracellular pathogens, and thus MHC class II genes,
96 detected positive associations between parasite burden and MHC diversity [10,30–32].

97

98 **2. Material and Methods**

99 (a) Database

100 We collected estimates of MHC-I diversity (i.e. loci number) from published databases
101 [3,12,33]. In total, we compiled 81 different estimates of MHC-I diversity with
102 corresponding blood parasite information (see final database in Table S1). For each bird
103 species with MHC-I diversity, we collected data on the number of detected blood parasite
104 lineages (hereafter lineages richness) of *Plasmodium*, *Haemoproteus* and *Leucocytozoon*
105 parasites using the MalAvi database [29], (accessed on 11th June 2021. Moreover, given
106 that the number of parasite lineages detected in a host is strongly dependent on sampling
107 effort, we also extracted the number of publications (i.e. total number of studies exploring
108 the given parasite genus in each particular host, see Table S2) and the total number of
109 individuals tested for the given haemosporidian genus in each bird species. When data
110 about the number of individuals tested was missing in the MalAvi database, this
111 information was collected directly from the referenced publications. Given that body size is
112 correlated with both parasite diversity and MHC diversity [12], we also collected
113 information on species-specific body masses from literature [12].

114

115 (b) Statistical analyses

116 In order to explore the effect of sampling effort, we tested the association between parasite
117 lineages richness and indicators of sampling effort (i.e. number of individuals or number of
118 publications) for each parasite genus separately and overall (i.e. combining all three genera
119 of blood parasites). Linear regressions indicated that the number of publications was a
120 considerably and consistently better predictor of parasite lineages richness than the number
121 of individuals inspected in all three inspected parasite genera, as well as for overall
122 haemosporidian lineages richness (appendix SI: figure S1). Therefore, we used the number
123 of publications as covariate in all subsequent analysis to control for sampling effort.

124

125 To test for associations between MHC-I diversity and blood parasite diversity, we
126 constructed phylogenetic generalized linear mixed model, using a Bayesian approximation
127 in the R package ‘*MCMCglmm*’ [34]. We used parasite lineages richness as dependent
128 variables (separately for each genus, and overall haemosporidian lineages richness) in
129 models with poisson error distribution [34]. Models included MHC-I diversity, species
130 body mass and the number of publication of the respective group of blood parasites as
131 covariates. MHC-I diversity data was methodologically heterogeneous, due to a large
132 variety of genotyping methods used to quantify it (e.g., cloning, 454 pyrosequencing, long-
133 reads, see table S1). Given that these methods frequently provide divergent results [33,35],
134 we included genotyping method as a random factor in the models. Moreover, MHC-I
135 diversity was repeatedly assessed in some species using the same genotyping method,
136 providing slightly conflicting estimates. Given that the accuracy of these estimates is
137 difficult to determine, we included all estimates in the models, but using species as a
138 random factor to control for pseudoreplication. Phylogeny was included in all models to
139 control for the shared evolutionary history of the host species. We used weakly informative
140 priors in all models [34]. Model convergence and absence of auto-correlation was assessed
141 by visual examination of the posterior parameter distributions. Since MHC diversity might
142 not be linearly related to parasite burden, we also tested quadratic effects in these models,
143 by incorporating MHC class I diversity as second-degree orthogonal polynomials. In
144 addition, because it is often ill-advised to combine data from various genotyping methods
145 [11,12,36], we also performed models separately for the two most frequently used
146 genotyping methods (cloning: n = 22 records, 21 species; 454 pyrosequencing: n = 35
147 records, 22 species). The limited number of species assessed by the other genotyping
148 methods did not allow separate analysis (n species \leq 9 for all other methods). For models,
149 only using cloning or pyrosequencing-based studies, we used the same MCMCglmm model

150 structure as described above but without the genotyping method random factor. Genotyping
151 effort can influence estimates of loci diversity, therefore to confirm the lack of such bias in
152 our results, we performed sensitivity analysis using the number of genotyped individuals as
153 model weights. All results were highly consistent irrespective of control for genotyping
154 effort (Table S6).

155

156 To account for phylogenetic non-independence we used trees from <http://birdtree.org>
157 [37]. We downloaded 1000 random trees using the Hackett backbone tree [38], and
158 calculated a rooted, ultrametric consensus tree using the SumTrees software [39]. All
159 statistical analyses were conducted using R version 3.6.3 [40].

160

161 **3. Results**

162 We compiled complete data on parasite lineages richness and MHC-I diversity for 54 bird
163 species, from 29 families and 7 orders, with *Passeriformes* being the most represented ($n =$
164 39 species; appendix SI: table S1). MHC class I loci numbers in our database varied widely,
165 from one to 33 loci. MHC-I diversity was highly divergent in species repeatedly genotyped
166 using different methods (e.g. *Acrocephalus arundinaceus*, cloning: 4 loci, 454
167 pyrosequencing: 9-10 loci). Cloning generally detected less MHC class I loci than 454
168 pyrosequencing (1-6, and 4-23 respectively). Observed parasite lineages richness also
169 varied greatly across host species (*Plasmodium*: 0-38; *Haemoproteus*: 0-42; *Leucocytozoon*
170 0-45; All blood parasites genera: 1-78).

171

172 The overall analysis, with genotyping method included as random factor (appendix SI: table
173 S3a) revealed no association between MHC-I diversity and any of the three haemosporidian
174 genera (*Plasmodium*: $p = 0.578$, *Haemoproteus*: $p = 0.467$, *Leucocytozoon*: $p = 0.356$), or in

175 overall blood parasite lineages richness ($p=0.533$). None of the quadratic effects of MHC
176 class I diversity were significant (Table S3b).

177

178 Models based on cloning assessment of MHC-I diversity (appendix SI: table S4) indicated
179 that a higher MHC-I diversity was associated with a significantly lower lineages richness of
180 *Plasmodium* (posterior mean = - 0.47, $p = 0.0161$; figure 1a), *Haemoproteus* (posterior
181 mean = -0.51, $p = 0.0148$; figure 1b), and overall haemosporidian lineages richness
182 (posterior mean = -0.39, $p = 0.0120$, figure 1d). No association was found between MHC-I
183 diversity and *Leucocytozoon* lineages richness (posterior mean = -0.05, $p = 0.9047$; figure
184 1c). In contrast, MHC diversity quantified using 454 pyrosequencing, revealed no
185 correlation between MHC-I diversity and *Plasmodium* (posterior mean = -0.01, $p =$
186 0.5843), *Haemoproteus* (posterior mean = -0.01, $p = 0.5897$), *Leucocytozoon* (posterior
187 mean = -0.05, $p = 0.1446$), or overall haemosporidian lineages richness (posterior mean = -
188 0.01, $p = 0.4264$, appendix SI: figure S2a-d, table S5).

189

190 **4. Discussion**

191 Here we performed a cross-species comparative analysis on MHC-I loci diversity in birds
192 and explored its association with the diversity of intracellular blood parasites infecting
193 these hosts. We did not detect an overall association between MHC-I diversity and blood
194 parasite diversity across species, but methodological heterogeneity in MHC genotyping
195 limits the reliability of these combined analyses [41]. On the contrary, analysis restricted to
196 cloning assessment of MHC-I diversity (but not 454 pyrosequencing) indicated that high
197 MHC-I diversity is associated with lower blood parasite diversity, regarding overall
198 haemosporidian, *Plasmodium* and *Haemoproteus*, but not *Leucocytozoon* lineages richness.

199

200 Comparative studies exploring the link between MHC class II and extracellular parasites
201 (helminths or ectoparasites) indicated that high parasite diversity was positively associated
202 with MHC nucleotide [30], or allelic diversity [31]. Bolnik et al. [42] however found a
203 negative correlation between MHC class II diversity and overall microbial diversity. One
204 recent study focusing for the first time on MHC loci number found a positive association
205 between helminth diversity and MHC class II [32]. Positive associations are commonly
206 explained by the benefit of maintaining high MHC diversity under strong parasite pressure.
207 Contrary to these results, our study points out a different dynamic linking intracellular
208 blood parasite burden and MHC-I diversity. We show that MHC-I diversity and blood
209 parasite richness is not positively, but rather negatively correlated, indicating that high
210 MHC-I diversity may provide qualitative resistance against diverse avian haemosporidian
211 parasites. Experimental studies support the possibility of full resistance against strains of
212 blood parasites [17]. In fact, after inoculation with a generalist *Plasmodium* lineage (SGS1),
213 bird species showed strikingly different parasite burdens, varying from full resistance or to
214 high susceptibility [17]. The role of MHC protein contributing to this resistance is
215 supported by the fact that individual flycatchers with high number of functional MHC
216 alleles were shown to have lower probability of malarial infection [43]. Other studies
217 demonstrate that the presence of specific MHC alleles could significantly decrease
218 probabilities of being infected by certain blood parasite strains [23,24]. Contrasting results
219 between parasite burden and MHC class I or class II diversity might be explained by
220 various non-exclusive factors: (i) the distinct evolutionary history of these genes and their
221 capacity to affect resistance and/or tolerance [12,41,44], (ii) the highly divergent species
222 composition of the mentioned studies (e.g. patterns detected across broad taxonomic scales
223 might not be present with narrow taxonomic coverage and vice versa), and (iii) the different

224 association of MHC diversity to different parasite groups (e.g. MHC class II diversity
225 relates negatively to bacterial but positively to helminth diversity). Additional studies are
226 needed to elucidate the mechanisms behind these divergent associations between MHC and
227 pathogen diversity.

228

229 Our results indicating fewer intracellular pathogens in host species with more MHC-I loci
230 support the heterozygote advantage hypothesis, which relies on the advantage provided by
231 heterozygosity of the MHC alleles, through the recognition of a wider range of antigens
232 compared to homozygotes. While it was suggested that pathogen richness alone seems
233 insufficient to explain the maintenance of extremely high MHC diversity (especially in
234 some passerines) [25], our results (restricted to cloning assessment of MHC) show a strong
235 correlation between MHC and parasite diversity. Importantly however, our results indicate
236 that the association between MHC-I diversity and parasite lineages richness is not
237 consistent when different genotyping techniques are used. The reason for this discrepancy
238 might be manifold. First, cloning quantification of MHC-I diversity in our database covered
239 a relatively wide taxonomic range (*Galliformes* to *Passeriformes*), while 454
240 pyrosequencing was only applied in passerines. It is thus possible that pathogen-mediated
241 evolution contributed to major taxonomic differences in MHC loci numbers, but different
242 selection processes are at play at the narrower taxonomic scales of e.g. passerines. The
243 latter is also supported by the greatly accelerated MHC duplication rate in songbirds, which
244 is unlikely to be the result of parasite-mediated selection alone [12]. Second, it is now
245 known that significantly fewer MHC class I alleles are expressed than present in the
246 genome [3], which is particularly concerning in species with highly duplicated MHC genes
247 such as many songbirds [3,11,12]. Non-expressed MHC alleles (pseudogenes) are
248 particularly problematic while using genotyping methods relying on genomic DNA

249 assembled from short segments [3], such as pyrosequencing, which potentially inflates
250 estimated of copy numbers. Consistently, pyrosequencing detected higher MHC loci than
251 cloning in all species genotyped by both techniques. Third, the association between MHC-I
252 diversity and parasite burden is not always linear [26], sometimes indicating a negative
253 association with moderate increase in MHC diversity, but not across high MHC diversity
254 ranges. Consequently, an initial decline in parasite burden with moderate increase in MHC
255 diversity (e.g. cloning analyses: loci number varies from 1 to 6) does not exclude the
256 possibility of a different association at high loci numbers (e.g., analyses restricted to
257 pyrosequencing: loci number varies from 4 to 23). Indeed, high MHC diversity can lead to
258 a significant reduction of the T cell receptor repertoire, having detrimental effects on the
259 efficiency of the immune response [45].

260

261 Overall, these results indicate a potentially important role of intracellular parasites in
262 shaping cross-species variance in MHC-I diversity. Nonetheless, evidence is mixed when
263 using different genotyping techniques, highlighting the need for better quality data on MHC
264 diversity to better understand immune gene evolution and selection shaping this. We urge
265 future research to quantify diversity in expressed MHC loci and to benefit from advanced
266 genotyping technologies, such as long-read sequencing.

267

268 **Data accessibility.**

269 All data are available in Table S1. Data and all code used to generate the results will be
270 made available in the Dryad Digital Repository upon acceptance.

271

272 **Authors' contributions.**

273 O.V. & C.L. wrote the manuscript. O.V. performed the comparative analysis. C.L. and
274 M.G. designed the analysis. All authors contributed to revisions and approved the final
275 version.

276

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288

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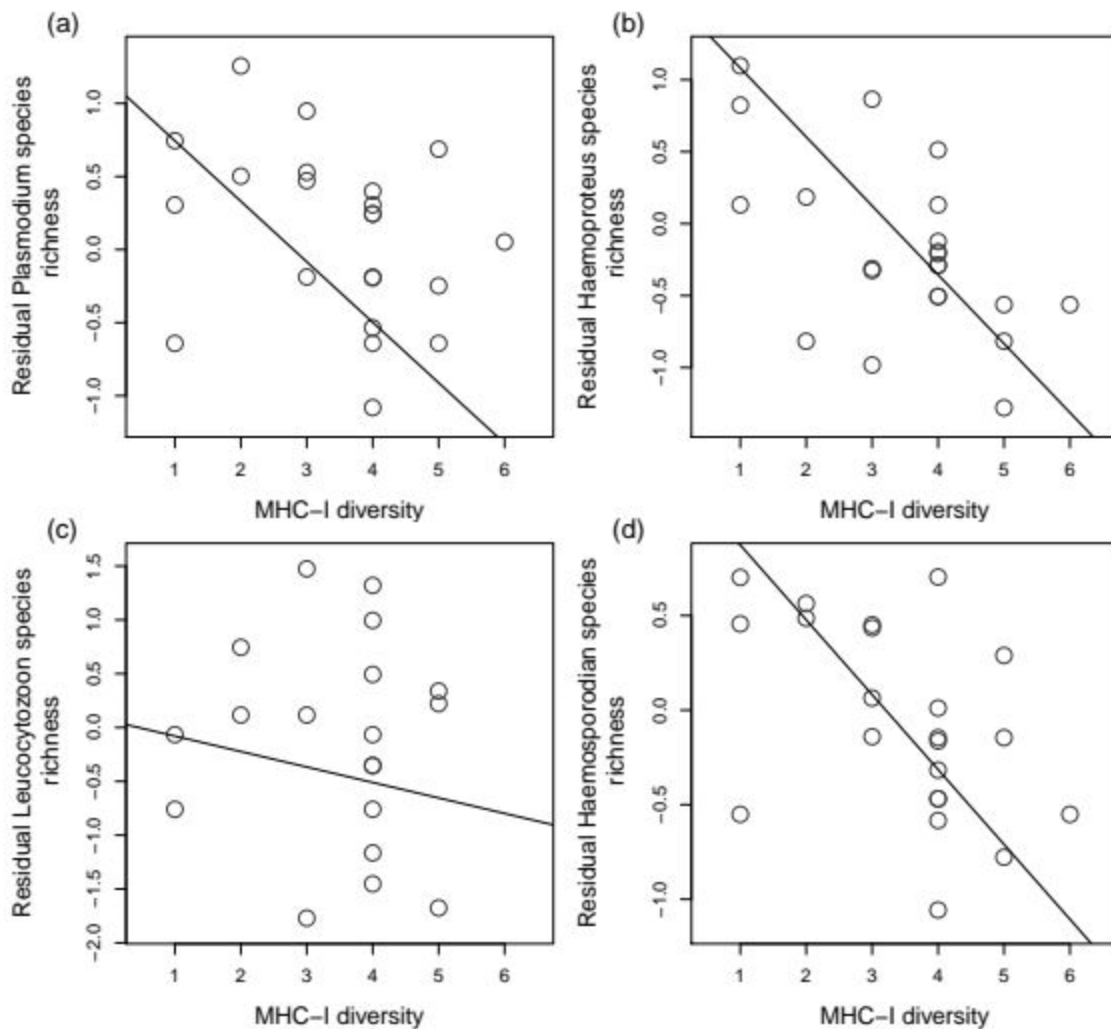
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- 420
- 421

422 **Figure 1.** Association between residual blood parasite species richness and MHC-I
423 diversity for (a) *Plasmodium*, (b) *Haemoproteus*, (c) *Leucocytozoon* and (d) overall
424 haemosporidian lineages richness. Parasite diversity residuals were obtained from a log-log
425 linear regressions between parasite lineages richness (dependent) and research effort
426 (explanatory). Slopes were obtained from phylogenetic MCMCglmms with poisson error
427 distribution between parasite lineages richness and research effort as well as MHC-I
428 diversity.



430

1 **Avian blood parasite richness decreases with MHC class I loci number**

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3

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19

20 **Abstract**

21 Major Histocompatibility Complex (MHC) genes are among the most polymorphic in the
22 vertebrate genome. The high allele diversity is believed to be maintained primarily by
23 sexual and pathogen-mediated balancing selection. The number of MHC loci also varies
24 greatly across vertebrates, most notably across birds. MHC proteins play key roles in
25 presenting antigens on the cell surface for recognition by T cells, with class I proteins

26 specifically targeting intracellular pathogens. Here we explore the hypothesis that MHC
27 class I diversity (measured as loci number) co-evolves with haemosporidian parasite burden
28 of the host. Using data on 54 bird species we demonstrate that high MHC class I diversity is
29 associated with significantly lower richness of *Plasmodium*, *Haemoproteus* as well as
30 overall haemosporidian parasite lineages, the former thus indicating a more efficient
31 protection against intracellular pathogens. Nonetheless, the latter associations were only
32 detected when MHC diversity was assessed using cloning and not 454 pyrosequencing-
33 based studies, nor across all genotyping methods combined. Our results indicate that high
34 MHC class I diversity might play a key role in providing qualitative resistance against
35 diverse haemosporidian parasites in birds, but further clarification is needed for the origin
36 of contrasting results when using different genotyping methods for MHC loci
37 quantification.

38

39 **Keywords**

40 Haemosporidians, copy number variation, parasite richness, pathogen-mediated selection,
41 comparative analyses, MHC diversity

42

43 **1. Introduction**

44 The Major Histocompatibility Complex (MHC) is known to be the most variable gene
45 group in vertebrates, both in terms of allelic diversity and gene number [1]. MHC genes
46 code for cell surface glycoproteins that bind to antigenic peptides and present them to cells
47 of the immune system, initiating adaptive immune responses. Proteins encoded by the
48 MHC genes ensure the immune presentation of a broad spectrum of peptides, both derived
49 from the intracellular (class I proteins) or extracellular (class II proteins) space [2]. High
50 MHC diversity, reflected by high allele diversity or loci number, is often related to the

51 ability to present a wider repertoire of antigens to the immune system, thus representing a
52 genetic marker of disease resistance [3] but see [4]. Several, mutually non-exclusive
53 hypotheses have been put forward to explain the maintenance of high MHC diversity, such
54 as the heterozygote advantage (i.e., MHC diversity conferring disease resistance), negative
55 frequency-dependent selection (benefit of rare MHC alleles in pathogen detection) or
56 fluctuating selection (spatial or temporal change in the selective advantage of MHC alleles)
57 [5,6].

58

59 The number of MHC loci varies greatly across vertebrates, being the result of a complex
60 evolutionary history, involving gene duplications and translocations [7,8]. For example,
61 species from the Galliformes order possess only two MHC class I genes [9,10], which is
62 considerably lower than in other bird lineages [11,12], such as passerines. Several studies
63 reported that a low number of MHC loci could represent the ancestral state in birds, and
64 that the highest diversification in copy numbers occurred relatively late in the avian
65 radiation, reaching its highest diversity in passerines [12]. While, parasite-mediated
66 selection has been considered as the most prominent component driving MHC
67 diversification [13], it is now widely accepted that in addition to the pathogen burden,
68 sexual selection and risk of developing autoimmune diseases or immunopathologies may
69 together shape the evolution of an optimal rather than maximal MHC diversity [3,4,13–15].

70

71 Malaria and closely related haemosporidian parasites are intensively investigated vector-
72 borne parasites in birds, partly because of the high diversity of hosts they are able to infect,
73 and their nearly worldwide distribution [16]. A series of experimental studies [17–21], have
74 demonstrated the substantial costs associated with haemosporidian infection, in terms of

75 reproductive success, health condition and survival. Hence, immunological adaptations
76 targeting and eliminating such infections can provide considerable fitness benefits. Key
77 components of these defenses are the MHC proteins. Nonetheless, knowledge on the co-
78 evolution of MHC diversity and avian haemosporidian parasite burden across species
79 remains limited [22–26]. However, other host-parasite systems found strong evidences that
80 specific MHC alleles confer resistance to pathogens [27,28].

81

82 With the increasing use of molecular tools, a large number of bird species have been
83 recently screened for haemosporidian parasites. The MalAvi database represents a unified
84 database compiling these data, covering genetic and geographical data of avian blood
85 parasites (*Plasmodium*, *Haemoproteus*, *Leucocytozoon* genera). It currently encompasses
86 more than 14,400 records with 4,520 lineages detected in more than 2,100 host species
87 [29]. Taking advantage of this unique database, here we explore whether MHC diversity
88 co-evolves with haemosporidian lineages richness. Given that haemosporidian parasites are
89 obligate intracellular parasites, here we focus on the MHC class I genes, exploring
90 relationships between gene copy numbers (hereafter MHC-I diversity) and blood parasite
91 lineages richness. Based on earlier species-specific studies on the link between MHC-I
92 allelic diversity and blood parasites [23,26] and according to the heterozygote advantage
93 hypothesis, we predict a negative association between MHC-I diversity and the diversity of
94 intracellular parasites across host species. Nonetheless, an opposite association can also be
95 predicted since studies focusing on extracellular pathogens, and thus MHC class II genes,
96 detected positive associations between parasite burden and MHC diversity [10,30–32].

97

98 **2. Material and Methods**

99 (a) Database

100 We collected estimates of MHC-I diversity (i.e. loci number) from published databases
101 [3,12,33]. In total, we compiled 81 different estimates of MHC-I diversity with
102 corresponding blood parasite information (see final database in Table S1). For each bird
103 species with MHC-I diversity, we collected data on the number of detected blood parasite
104 lineages (hereafter lineages richness) of *Plasmodium*, *Haemoproteus* and *Leucocytozoon*
105 parasites using the MalAvi database [29], (accessed on 11th June 2021. Moreover, given
106 that the number of parasite lineages detected in a host is strongly dependent on sampling
107 effort, we also extracted the number of publications (i.e. total number of studies exploring
108 the given parasite genus in each particular host, see Table S2) and the total number of
109 individuals tested for the given haemosporidian genus in each bird species. When data
110 about the number of individuals tested was missing in the MalAvi database, this
111 information was collected directly from the referenced publications. Given that body size is
112 correlated with both parasite diversity and MHC diversity [12], we also collected
113 information on species-specific body masses from literature [12].

114

115 (b) Statistical analyses

116 In order to explore the effect of sampling effort, we tested the association between parasite
117 lineages richness and indicators of sampling effort (i.e. number of individuals or number of
118 publications) for each parasite genus separately and overall (i.e. combining all three genera
119 of blood parasites). Linear regressions indicated that the number of publications was a
120 considerably and consistently better predictor of parasite lineages richness than the number
121 of individuals inspected in all three inspected parasite genera, as well as for overall
122 haemosporidian lineages richness (appendix SI: figure S1). Therefore, we used the number
123 of publications as covariate in all subsequent analysis to control for sampling effort.

124

125 To test for associations between MHC-I diversity and blood parasite diversity, we
126 constructed phylogenetic generalized linear mixed model, using a Bayesian approximation
127 in the R package ‘*MCMCglmm*’ [34]. We used parasite lineages richness as dependent
128 variables (separately for each genus, and overall haemosporidian lineages richness) in
129 models with poisson error distribution [34]. Models included MHC-I diversity, species
130 body mass and the number of publication of the respective group of blood parasites as
131 covariates. MHC-I diversity data was methodologically heterogeneous, due to a large
132 variety of genotyping methods used to quantify it (e.g., cloning, 454 pyrosequencing, long-
133 reads, see table S1). Given that these methods frequently provide divergent results [33,35],
134 we included genotyping method as a random factor in the models. Moreover, MHC-I
135 diversity was repeatedly assessed in some species using the same genotyping method,
136 providing slightly conflicting estimates. Given that the accuracy of these estimates is
137 difficult to determine, we included all estimates in the models, but using species as a
138 random factor to control for pseudoreplication. Phylogeny was included in all models to
139 control for the shared evolutionary history of the host species. We used weakly informative
140 priors in all models [34]. Model convergence and absence of auto-correlation was assessed
141 by visual examination of the posterior parameter distributions. Since MHC diversity might
142 not be linearly related to parasite burden, we also tested quadratic effects in these models,
143 by incorporating MHC class I diversity as second-degree orthogonal polynomials. In
144 addition, because it is often ill-advised to combine data from various genotyping methods
145 [11,12,36], we also performed models separately for the two most frequently used
146 genotyping methods (cloning: n = 22 records, 21 species; 454 pyrosequencing: n = 35
147 records, 22 species). The limited number of species assessed by the other genotyping
148 methods did not allow separate analysis (n species \leq 9 for all other methods). For models,
149 only using cloning or pyrosequencing-based studies, we used the same MCMCglmm model

150 structure as described above but without the genotyping method random factor. Genotyping
151 effort can influence estimates of loci diversity, therefore to confirm the lack of such bias in
152 our results, we performed sensitivity analysis using the number of genotyped individuals as
153 model weights. All results were highly consistent irrespective of control for genotyping
154 effort (Table S6).

155

156 To account for phylogenetic non-independence we used trees from <http://birdtree.org>
157 [37]. We downloaded 1000 random trees using the Hackett backbone tree [38], and
158 calculated a rooted, ultrametric consensus tree using the SumTrees software [39]. All
159 statistical analyses were conducted using R version 3.6.3 [40].

160

161 **3. Results**

162 We compiled complete data on parasite lineages richness and MHC-I diversity for 54 bird
163 species, from 29 families and 7 orders, with *Passeriformes* being the most represented ($n =$
164 39 species; appendix SI: table S1). MHC class I loci numbers in our database varied widely,
165 from one to 33 loci. MHC-I diversity was highly divergent in species repeatedly genotyped
166 using different methods (e.g. *Acrocephalus arundinaceus*, cloning: 4 loci, 454
167 pyrosequencing: 9-10 loci). Cloning generally detected less MHC class I loci than 454
168 pyrosequencing (1-6, and 4-23 respectively). Observed parasite lineages richness also
169 varied greatly across host species (*Plasmodium*: 0-38; *Haemoproteus*: 0-42; *Leucocytozoon*
170 0-45; All blood parasites genera: 1-78).

171

172 The overall analysis, with genotyping method included as random factor (appendix SI: table
173 S3a) revealed no association between MHC-I diversity and any of the three haemosporidian
174 genera (*Plasmodium*: $p = 0.578$, *Haemoproteus*: $p = 0.467$, *Leucocytozoon*: $p = 0.356$), or in

175 overall blood parasite lineages richness ($p=0.533$). None of the quadratic effects of MHC
176 class I diversity were significant (Table S3b).

177

178 Models based on cloning assessment of MHC-I diversity (appendix SI: table S4) indicated
179 that a higher MHC-I diversity was associated with a significantly lower lineages richness of
180 *Plasmodium* (posterior mean = - 0.47, $p = 0.0161$; figure 1a), *Haemoproteus* (posterior
181 mean = -0.51, $p = 0.0148$; figure 1b), and overall haemosporidian lineages richness
182 (posterior mean = -0.39, $p = 0.0120$, figure 1d). No association was found between MHC-I
183 diversity and *Leucocytozoon* lineages richness (posterior mean = -0.05, $p = 0.9047$; figure
184 1c). In contrast, MHC diversity quantified using 454 pyrosequencing, revealed no
185 correlation between MHC-I diversity and *Plasmodium* (posterior mean = -0.01, $p =$
186 0.5843), *Haemoproteus* (posterior mean = -0.01, $p = 0.5897$), *Leucocytozoon* (posterior
187 mean = -0.05, $p = 0.1446$), or overall haemosporidian lineages richness (posterior mean = -
188 0.01 , $p = 0.4264$, appendix SI: figure S2a-d, table S5).

189

190 **4. Discussion**

191 Here we performed a cross-species comparative analysis on MHC-I loci diversity in birds
192 and explored its association with the diversity of intracellular blood parasites infecting
193 these hosts. We did not detect an overall association between MHC-I diversity and blood
194 parasite diversity across species, but methodological heterogeneity in MHC genotyping
195 limits the reliability of these combined analyses [41]. On the contrary, analysis restricted to
196 cloning assessment of MHC-I diversity (but not 454 pyrosequencing) indicated that high
197 MHC-I diversity is associated with lower blood parasite diversity, regarding overall
198 haemosporidian, *Plasmodium* and *Haemoproteus*, but not *Leucocytozoon* lineages richness.

199

200 Comparative studies exploring the link between MHC class II and extracellular parasites
201 (helminths or ectoparasites) indicated that high parasite diversity was positively associated
202 with MHC nucleotide [30], or allelic diversity [31]. Bolnik et al. [42] however found a
203 negative correlation between MHC class II diversity and overall microbial diversity. One
204 recent study also focusing for the first time on MHC loci number found a positive
205 association between helminth diversity and MHC class II loci number and MHC class II
206 [32]. The Positive associations are commonly explained by the benefit of maintaining
207 high MHC diversity under strong parasite pressure. Contrary to these results, our study
208 points out a different dynamic linking intracellular blood parasite burden and MHC-I
209 diversity. We show that MHC-I diversity and blood parasite richness is not positively, but
210 rather negatively correlated, indicating that high MHC-I diversity may provide qualitative
211 resistance against diverse avian haemosporidian parasites. Experimental studies support the
212 possibility of full resistance against strains of blood parasites [17]. In fact, after inoculation
213 with a generalist *Plasmodium* lineage (SGS1), bird species showed strikingly different
214 parasite burdens, varying from full resistance or to high susceptibility [17]. The role of
215 MHC protein contributing to this resistance is supported by the fact that individual
216 flycatchers with high number of functional MHC alleles were shown to have lower
217 probability of malarial infection [43]. Other studies demonstrate that the presence of
218 specific MHC alleles could significantly decrease probabilities of being infected by certain
219 blood parasite strains [23,24]. Finally, contrasting results between parasite burden and
220 MHC class I or class II diversity might be explained by various non-exclusive factors: (i)
221 the distinct evolutionary history of these genes and their capacity to affect resistance and/or
222 tolerance [12,41,44], (ii) the highly divergent species composition of the mentioned studies
223 (e.g. patterns detected across broad taxonomic scales might not be present with narrow

224 ~~taxonomic coverage and vice versa), and (iii) the different association of MHC diversity to~~
225 ~~different parasite groups (e.g. MHC class II diversity relates negatively to bacterial but~~
226 ~~positively to helminth diversity). Additional studies are needed to elucidate the mechanisms~~
227 ~~behind these divergent associations between MHC and pathogen diversity. It appears that~~
228 ~~MHC class I copy numbers were primarily shaped by accelerated evolution ('burst') and~~
229 ~~stabilizing selection, while the evolution of MHC class II loci were likely governed by~~
230 ~~fluctuating selection and drift [12].~~

231

232 Our results indicating fewer intracellular pathogens in host species with more MHC-I loci
233 support the heterozygote advantage hypothesis, which relies on the advantage provided by
234 heterozygosity of the MHC alleles, through the recognition of a wider range of antigens
235 compared to homozygotes. While it was suggested that pathogen richness alone seems
236 insufficient to explain the maintenance of extremely high MHC diversity (especially in
237 some passerines) [25], our results (restricted to cloning assessment of MHC) show a strong
238 correlation between MHC and parasite diversity. Importantly however, our results indicate
239 that the association between MHC-I diversity and parasite lineages richness is not
240 consistent when different genotyping techniques are used. The reason for this discrepancy
241 might be manifold. First, cloning quantification of MHC-I diversity in our database covered
242 a relatively wide taxonomic range (*Galliformes* to *Passeriformes*), while 454
243 pyrosequencing was only applied in passerines. It is thus possible that pathogen-mediated
244 evolution contributed to major taxonomic differences in MHC loci numbers, but different
245 selection processes are at play at the narrower taxonomic scales of e.g. passerines. The
246 latter is also supported by the greatly accelerated MHC duplication rate in songbirds, which
247 is unlikely to be the result of parasite-mediated selection alone [12]. Second, it is now
248 known that significantly fewer MHC class I alleles are expressed than present in the

249 genome [3], which is particularly concerning in species with highly duplicated MHC genes
250 such as many songbirds [3,11,12]. Non-expressed MHC alleles (pseudogenes) are
251 particularly problematic while using genotyping methods relying on genomic DNA
252 assembled from short segments [3], such as pyrosequencing, which potentially inflates
253 estimated of copy numbers. Consistently, pyrosequencing detected higher MHC loci than
254 cloning in all species genotyped by both techniques. Third, the association between MHC-I
255 diversity and parasite burden is not always linear [26], sometimes indicating a negative
256 association with moderate increase in MHC diversity, but not across high MHC diversity
257 ranges. Consequently, an initial decline in parasite burden with moderate increase in MHC
258 diversity (e.g. cloning analyses: loci number varies from 1 to 6) does not exclude the
259 possibility of a different association at high loci numbers (e.g., analyses restricted to
260 pyrosequencing: loci number varies from 4 to 23). Indeed, high MHC diversity can lead to
261 a significant reduction of the T cell receptor repertoire, having detrimental effects on the
262 efficiency of the immune response [453].

263

264 Overall, these results indicate a potentially important role of intracellular parasites in
265 shaping cross-species variance in MHC-I diversity. Nonetheless, evidence is mixed when
266 using different genotyping techniques, highlighting the need for better quality data on MHC
267 diversity to better understand immune gene evolution and selection shaping this. We urge
268 future research to quantify diversity in expressed MHC loci and to benefit from advanced
269 genotyping technologies, such as long-read sequencing.

270

271 **Data accessibility.**

272 All data are available in Table S1. Data and all code used to generate the results will be
273 made available in the Dryad Digital Repository upon acceptance.

274

275 **Authors' contributions.**

276 O.V. & C.L. wrote the manuscript. O.V. performed the comparative analysis. C.L. and
277 M.G. designed the analysis. All authors contributed to revisions and approved the final
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279

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291

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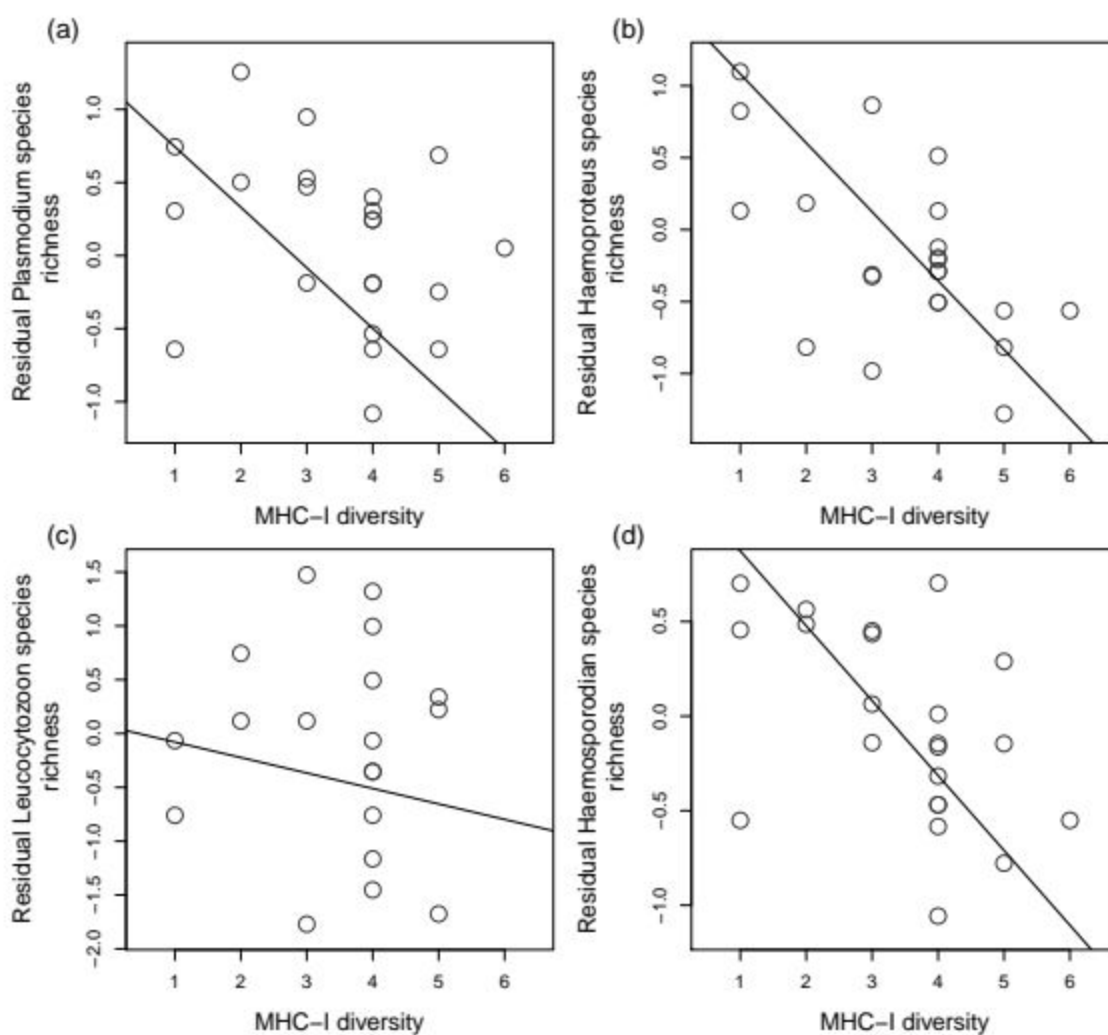
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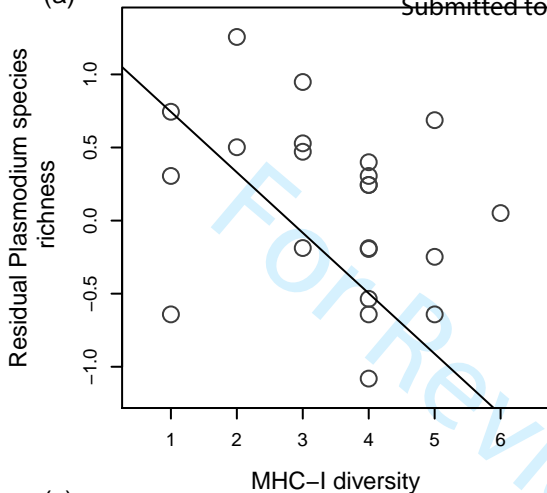
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425 **Figure 1.** Association between residual blood parasite species richness and MHC-I
426 diversity for (a) *Plasmodium*, (b) *Haemoproteus*, (c) *Leucocytozoon* and (d) overall
427 haemosporidian lineages richness. Parasite diversity residuals were obtained from a log-log
428 linear regressions between parasite lineages richness (dependent) and research effort
429 (explanatory). Slopes were obtained from phylogenetic MCMCglmms with poisson error
430 distribution between parasite lineages richness and research effort as well as MHC-I
431 diversity.

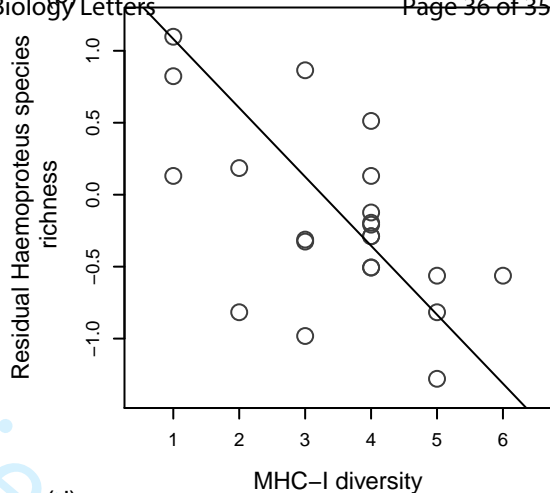


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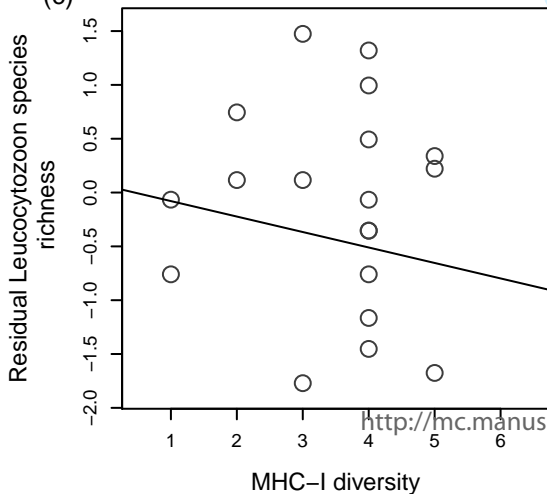
(a)



(b)



(c)



(d)

