

Coupling between tolerance and resistance differs between related *Eimeria* parasite species: implications for coevolution with their mouse hosts

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Authors contributions: AB, JP and EH designed the experiment and analysis. LD and JP provided the research material. AB, VHJD, JJ, VM and FB carried out the experiment. AB performed the analysis. AB and EH wrote the manuscript, with major contribution from JP and feedback from all the authors. Funding: This work was funded by the German Research Foundation (DFG) Grant [HE 7320/1-1] to EH. VHJ is an associated student of GRK 2046 funded by the DFG. The maintenance of wild-derived strains was supported by the ROSE program from Czech Academy of Sciences and the Czech Science Foundation (project 16-23773S) to JP.

Data accessibility: Code and data used for this article can be found at:

https://github.com/alicebalard/Article_RelatedParasitesResTol

23 **Abstract**

24 Resistance (host capacity to reduce parasite burden) and tolerance (host capacity to
25 reduce impact on its health for a given parasite burden) manifest two different lines of
26 defence. Tolerance can be independent from resistance, traded-off against it, or the
27 two can be positively correlated because of redundancy in underlying (immune)
28 processes. We here tested whether this coupling between tolerance and resistance
29 could differ upon infection with closely related parasite species. We tested this in
30 experimental infections with two parasite species of genus *Eimeria*. We measured
31 proxies for resistance (the (inverse of) number of parasite transmission stages
32 (oocysts) per gram of feces at the day of maximal shedding) and tolerance (the slope
33 of maximum relative weight loss compared to day of infection on number of oocysts
34 per gram of feces at the day of maximal shedding for each host strain) in four inbred
35 mouse strains and four groups of F1 hybrids belonging to two mouse subspecies,
36 *Mus musculus domesticus* and *M. m. musculus*. We found a negative correlation
37 between resistance and tolerance against *E. falciformis*, while the two are uncoupled
38 against *E. ferrisi*. We conclude that resistance and tolerance against the first parasite
39 species might be traded off, but evolve more independently in different mouse
40 genotypes against the latter. We argue that evolution of the host immune defences
41 can be studied largely irrespective of parasite isolates if resistance-tolerance coupling
42 is absent or weak (*E. ferrisi*) but host-parasite coevolution is more likely observable
43 and best studied in a system with negatively correlated tolerance and resistance
44 (*E. falciformis*).

45 **Keywords:** Resistance, Tolerance, *Eimeria*, Coevolution

46 **Introduction**

47 Host defence mechanisms evolve to alleviate the detrimental effect of parasites. They
48 can be categorised into two components: resistance and tolerance (Råberg et al.,
49 2009). Resistance is the ability of a host to reduce parasite burden, resulting from
50 defence against parasite infection or proliferation early after infection
51 (Schmid-Hempel, 2013). The negative effect of resistance on parasite fitness can
52 lead to antagonistic coevolution. According to theoretical models, fluctuating host and
53 parasite genotypes arise, and balancing selection maintains resistance alleles
54 polymorphic (Boots et al., 2008; Roy & Kirchner, 2000). Resistance has been the
55 classical "catch all" measure for host-parasite systems, but recently it has been shown
56 to be incomplete, especially with respect to potential fitness effects on the host
57 (Kutzer & Armitage, 2016; Råberg et al., 2009).

58 Disease tolerance (not to be confused from "immunological tolerance",
59 unresponsiveness to self antigens; Medzhitov et al., 2012) is the ability of the host to
60 limit the impact of parasite on its fitness (Kutzer & Armitage, 2016; Råberg et al.,
61 2009; Vale & Little, 2012). By potentially providing a longer-living niche, this defence
62 mechanism improves, or at least does not deteriorate, the fitness of the parasite.
63 Tolerance alleles are thus predicted by theoretical models to evolve to fixation due to
64 positive feedback loops (Boots et al., 2008; Restif & Koella, 2004; Roy & Kirchner,
65 2000). From a mechanistic perspective tolerance alleviates direct or indirect damage
66 (e.g. excessive immune response underlying resistance against parasites, called
67 immunopathology; Graham et al., 2005) caused by parasites (Råberg et al., 2009).
68 Tolerance mechanisms include modulation of inflammatory response (Ayres &

69 Schneider, [2012](#)), tissue repair (stress response, damage repair and cellular
70 regeneration mechanisms; Soares et al., [2017](#)), and compensation of
71 parasite-induced damage by increase of reproductive effort (Baucom & de Roode,
72 [2011](#)). The resulting metabolic costs of resistance and tolerance, with and without
73 parasite infection, determine the optimal (steady state and infection inducible) extent
74 and of both immune defences (Sheldon & Verhulst, [1996](#)).

75 Resistance and tolerance can be positively associated if they involve the same
76 metabolic pathway, as was shown in the plant model *Arabidopsis thaliana* in response
77 against herbivory (Mesa et al., [2017](#)). In animals, genetic association studies of
78 resistance and tolerance of *Drosophila melanogaster* against the bacterium
79 *Providencia rettgeri* have shown positively correlated genetic effects, as the same loci
80 were associated with changes of both traits in the same direction (Howick & Lazzaro,
81 [2017](#)).

82 Nevertheless, resistance and tolerance can also be genetically and physiologically
83 independent, involving different proximate mechanisms. Lack of correlation between
84 both defences was shown for example in monarch butterflies (*Danaus plexippus*)
85 infected by the protozoan parasite *Ophryocystis elektroscirrha*. This study found
86 genetic variation in resistance between butterflies families, but a fixed tolerance
87 (Lefèvre et al., [2010](#)). Similarly, no correlation could be found between resistance and
88 tolerance for the fish *Leuciscus burdigalensis* in response to infection with its parasite
89 *Tracheliastes polycolpus*. The authors explain the decoupling of both defences by the
90 fact that, in this system, tolerance likely involves wound repair rather than immune
91 regulation, making resistance and tolerance mechanisms independent (Mazé-Guilmo

92 et al., [2014](#)).

93 Eventually, in other systems, resistance and tolerance have been found negatively
94 correlated. For examples, inbred laboratory mouse strains lose weight upon infection
95 with *Plasmodium chabaudi*. The extent of this impact on host health is negatively
96 correlated with the peak number of parasites found in the blood (Råberg et al., [2007](#)),
97 meaning that mouse strains with higher resistance present lower tolerance. Similarly,
98 infections of sea trout (*Salmo trutta trutta*) and Atlantic salmon (*Salmo salar*) with the
99 trematode *Diplostomum pseudospathaceum* showed that resistance and tolerance
100 were negatively correlated when assessing mean levels of both traits in different host
101 populations (Klemme & Karvonen, [2016](#)). This is interpreted as a result of trade-off
102 between resistance and tolerance (Råberg et al., [2009](#); Restif & Koella, [2004](#);
103 Sheldon & Verhulst, [1996](#)).

104 We have seen that depending on the system studied resistance and tolerance can be
105 (1) uncoupled (independent), (2) positively correlated (involving same genes and
106 mechanisms), or (3) negatively correlated (traded-off). Theoretical models show that
107 coupling between resistance and tolerance (or absence thereof) could depend not
108 only on the host but also on the parasite (Carval & Ferriere, [2010](#)). Here we tested
109 this hypothesis. More precisely, we asked whether there could be differences in the
110 resistance-tolerance coupling upon infection of one host type with two closely related
111 parasite species. To answer this question, we infected four inbred mouse strains and
112 four groups of F1 hybrids representative of two house mouse subspecies,
113 *M. m. domesticus* and *M. m. musculus*, with three parasite isolates representative of
114 two naturally occurring parasite species, the protozoan parasite *Eimeria ferrisi* and

115 *E. falciformis* (Jarquín-Díaz et al., 2019). *Eimeria* spp. are monoxenous parasites that
116 expand asexually and reproduce sexually in intestinal epithelial cells, leading to
117 malabsorption of nutrients, tissue damage and weight loss (Chapman et al., 2013).
118 The evolutionary history of these different *Eimeria* species in the two house mouse
119 subspecies is unknown and it is unclear whether subspecies-specific adaptation
120 exists in one or the other.

121 We tested if coupling between resistance and tolerance differs between both parasite
122 species and discussed the implication for parasite-host coevolution. Additionally, as
123 coevolving hosts and parasites can adapt to their antagonist, we tested adaptation to
124 the host subspecies (hereafter "host adaptation") of *E. ferrisi* to *Mus musculus*, using
125 a parasite isolated in a *M. m. domesticus* host and one in a *M. m. musculus* host.
126 Higher parasite fitness of one isolate in one of the two hosts and inversely for the
127 second isolate, or higher host fitness upon infection with one of the two parasite
128 isolates and inversely for the second isolate, would be indirect evidence for
129 coevolution of this parasite with *Mus musculus*.

130 **Material and methods**

131 **1. Parasite isolates**

132 The three parasite isolates used in this study were isolated from feces of three different
133 *M. m. domesticus*/*M. m. musculus* hybrid mice captured in Brandenburg, Germany, in
134 2016 (capture permit No. 2347/35/2014). The parasite isolates belong to both the most
135 prevalent *Eimeria* species in this area, namely *E. ferrisi* (isolates Brandenburg64 and
136 Brandenburg139) and *E. falciformis* (isolate Brandenburg88)(Jarquín-Díaz et al., 2019).

Isolate Brandenburg64 was isolated in a 92% *M. m. domesticus* individual (hybrid index (HI) = 0.08: Proportion of *M. m. musculus* alleles in a set of 14 diagnostic markers, see Balard et al. (2020)), isolate Brandenburg139 in a 85% *M. m. musculus* (HI=0.85) and isolate Brandenburg88 in a 80% *M. m. domesticus* (HI=0.2). Pre-patency and the peak day of parasite shedding for these isolates were estimated during infection in NMRI laboratory mice (Al-khlifeh et al., 2019) which were also used for serial passaging of the isolates. Parasite infective forms (oocysts) were recovered by flotation in saturated NaCl solution followed by washing and observation under light microscope (following the protocol described in Clerc et al. (2019)) and stored at room temperature in 1mL of 2% potassium dichromate for a maximum of 2 months before infection of the wild-derived mice. Oocysts were allowed to sporulate 10 days before infection in a water bath at 30°C.

2. Mouse groups

We used four wild-derived inbred mouse strains from which we generated four groups of F1 hybrids. Two parental strains represented *M. m. domesticus*: **SCHUNT** (Locality: Schweben, Hessen, Germany [N: 50° 26', E: 9° 36'] (Martincová et al., 2019)) and **STRA** (Locality: Straas, Bavaria, Germany [N: 50° 11', E: 11° 46'] (Piálek et al., 2008)), and two derived from *M. m. musculus*: **BUSNA** (Locality: Buškovice, Bohemia, Czech Republic [N: 50° 14', E: 13° 22'] (Piálek et al., 2008)) and **PWD** (Locality: Kunratice, Bohemia, Czech Republic [N: 50° 01', E: 14° 29'] (Gregorová & Forejt, 2000)). The four groups of F1 hybrids consisted of two intrasubspecific hybrids (**SCHUNTxSTRA** and **PWDxBUSNA**) and two intersubspecific hybrids (**STRAxBUSNA** and **SCHUNTxPWD**)(Figure 1). Age of the mice at the time of

160 infection ranged between 5.6 and 21.4 weeks. All mouse strains and F1 hybrids were
161 obtained from the Institute of Vertebrate Biology of the Czech Academy of Sciences in
162 Studenec (licence number 61974/2017-MZE-17214; for further details on strains see
163 <https://housemice.cz/en>).

164 Parasites of the *Eimeria* genus are known to induce host immune protection against
165 reinfection (Rose et al., 1992; Smith & Hayday, 2000). To ensure that our mice were
166 *Eimeria*-naïve, mouse fecal samples were tested before infection for the presence of
167 *Eimeria* spp. oocysts by flotation in saturated NaCl solution followed by washing and
168 observation under light microscope.

169 **3. Experimental infection**

170 Mice were kept in individual cages during infection. Water and food (SNIFF,
171 Rat/Mouse maintenance feed 10 mm) were provided *ad libitum* supplemented with 1
172 g of sunflower and barley seeds per day. Mice were orally infected with 150
173 sporulated oocysts of one *Eimeria* isolate suspended in 100 μ l phosphate-buffer saline
174 (PBS) and monitored daily until their sacrifice by cervical dislocation at time of
175 regression of infection (reduction of oocyst output). Individuals presenting severe
176 health deficiency and/or a weight loss approaching 18% relative to their starting
177 weight were sacrificed earlier at defined humane end points (experiment license Reg.
178 0431/17). Weight was recorded and feces collected on a daily basis. Fecal pellets
179 were collected every day from each individual cage and suspended in 2% potassium
180 dichromate. Parasite oocysts were recovered using NaCl flotation (see above).

181 All individuals were negative for *Eimeria* at the beginning of our experiment (before

infection of first batch, as described in the next paragraph). In total, 168 mice were infected. Mice were randomly allocated to experimental groups ensuring homogeneous distribution of ages and sexes between groups. Our experiments were conducted in four (partially overlapping) consecutive batches for logistical reasons. The first two batches were infected with the two *E. ferrisi* isolates (Brandenburg64 and Brandenburg139), the third and fourth by one *E. ferrisi* isolate (Brandenburg64) and one *E. falciformis* isolate (Brandenburg88). Our experimental design is summarized in **Table 1** (chronology of experimental batches can be scrutinized in **Supplementary Table S1**).

Nematode infection is common in breeding facilities (Baker, 1998) and could interact with *Eimeria* (Clerc et al., 2019). We surveyed for their presence and nematode eggs were observed in flotated feces of mice belonging to all genotypes before the experiment. Despite treatment of the first infection batch of mice (B1, 22 mice) with anthelmintics (Profender®, Bayer AG, Levekusen, Germany) following the protocole of Mehlhorn et al. (2005), nematodes were still detected with PCR (following the protocole of Floyd et al. (2005)) in randomly sampled fecal samples a week later. We therefore decided not to treat mice of the following infection batches. Moreover, we observed *Eimeria* oocysts in the feces of 28 mice belonging to the last experimental batch (batch B4) at the day of infection, likely due to cross-contamination between batches. For following statistical analyses, we considered along with the full data set (N=168) a conservative data set in which cross-contaminated animals and animals treated by anthelmintic were removed (N=118). Results obtained on the conservative data set can be found in **Supplementary Material S2**. Despite differences in significance due to a lower statistical power, the main conclusions of our

analyses were consistent with those obtained on the main data set.

4. Statistical analyses

4.1. Choice of proxies for resistance, impact of parasite on host and tolerance

As resistance is the capacity of a host to reduce its parasite burden, it is usually estimated by the inverse of infection intensity (Råberg et al., 2009). Pre-patency (the time to shedding of infectious stages, so called oocysts) is longer for *E. falciformis* (7 days) than for *E. ferrisi* (5 days) (Al-khlifeh et al., 2019). Therefore, as a proxy of (inverse of) resistance we used the number of oocysts per gram of feces (OPG) at the day of maximal shedding. Using the Spearman's non-parametric rank correlation test, we found this measurement to be tightly correlated with the sum of oocysts shed throughout the experiment (Spearman's $\rho=0.93$, $N=168$, $P<0.001$). Due to the aggregation characteristic of parasites (Shaw & Dobson, 1995), the appropriate distribution for maximum number of OPG was found to be the negative binomial distribution. This was confirmed based on log likelihood, AIC criteria and goodness-of-fits plots (density, CDF, Q-Q, P-P plots; R packages MASS (Venables & Ripley, 2002) and fitdistrplus (Delignette-Muller & Dutang, 2015)).

Both parasite species provoke inflammation, cellular infiltration, enteric lesions, diarrhea, and ultimately weight loss (Al-khlifeh et al., 2019; Ankrom et al., 1975; Ehret et al., 2017; Schito et al., 1996). Therefore, the impact of parasites on host health was measured as the maximum relative weight loss compared to day 0 (body weight measured at the start of the experimental infection). For mice sacrificed at humane end points before the end of the experiment, last weight of the living animal was used.

228 This weight (loss) can be expected to be a very conservative estimate for our
229 analyses (rendering tolerance conservatively low for these animals, which might have
230 lost more weight if not sacrificed).

231 Tolerance is usually defined as a reaction norm, i.e. the regression slope of host fitness
232 (or health condition if that is the parameter of interest) on infection intensity per host
233 genotype (Råberg et al., 2009; Simms, 2000). Thus tolerance was assessed as the
234 slope of maximum relative weight loss compared to day 0 on number of OPG at the
235 day of maximal shedding, within each mouse group and for each parasite isolate. A
236 steep slope indicates a low tolerance (high weight lost for a given parasite burden).

237 **4.2. Statistical modelling**

238 Maximum OPG and relative weight loss were modelled separately as a response of
239 either mouse group, parasite isolate and their interaction. We used a negative binomial
240 generalised linear model for maximum OPG, and a linear model for relative weight loss.
241 For tolerance, we performed a linear regression with null intercept (as each mouse was
242 controlled against itself at start of the experiment, before losing weight or shedding
243 parasite), modelling relative weight loss as a response of maximum OPG interacting
244 either mouse group, parasite isolate and their interaction. To test the significance of
245 the marginal contribution of each parameter to the full model, each parameter was
246 removed from the full model, and the difference between full and reduced model was
247 assessed using likelihood ratio tests (G).

248 For each of our model, we also asked within each parasite isolate if the response
249 differed between mouse groups using likelihood ratio tests (G) as described above. Of

250 note, four mice infected by *E. falciformis* isolate Brandenburg88 did not shed any
251 oocysts as death occurred at or one day before the peak of oocysts shedding in other
252 mice. For this reason, we modelled maximum OPG for mice infected with this parasite
253 using a zero-inflated negative binomial (ZINB) generalised linear model, after verifying
254 that it provided a better fit than the simple negative binomial based on log likelihood
255 and AIC criteria.

256 4.3. Test of host adaptation

257 Host adaptation of *E. ferrisi* was tested using two isolates (the "Western"
258 Brandenburg64 and "Eastern" Brandenburg139) and our four parental mouse strains
259 (the two *M. m. domesticus* Western SCHUNT and STRA, and the two *M. m. musculus*
260 Eastern BUSNA and PWD). We hypothesised a possible host adaptation of *E. ferrisi*.
261 The prediction drawn from this would be that the Eastern parasite (*E. ferrisi* isolate
262 Brandenburg139) reproduces better in the matching Eastern mouse subspecies
263 (*M. m. musculus*) than in the Western one (*M. m. domesticus*), and similarly the
264 Western parasite (*E. ferrisi* isolate Brandenburg64) reproduce better in
265 *M. m. domesticus* than in *M. m. musculus*. Additionally, a higher tolerance of each
266 host infected by its matching parasite despite similar parasite reproductive output
267 could indicate increased host fitness, and host adaptation.

268 4.4. Test of coupling between resistance and tolerance

269 We tested coupling between resistance and tolerance for *E. ferrisi* and *E. falciformis*
270 using the isolates Brandenburg64 and Brandenburg88 and our eight mouse groups.

271 To test such coupling, one can assess the strength of correlation between measure of
272 resistance and measure of tolerance (Råberg et al., 2007). Of note, tolerance (in
273 absolute value) is measured as the slope α of the linear regression of parasite load (x)
274 on maximum relative weight loss (y) of equation $y = \alpha x + \beta$ (α being the slope and β
275 the intercept, 0 in our case). Therefore, tolerance is expressed as $\alpha = y/x - \beta/x$. As x
276 and y/x are by definition not independent, testing the correlation between resistance
277 and tolerance can lead to spurious correlation (Brett, 2004). To alleviate the dangers
278 of this statistical artifact, we additionally tested differences in resistance, impact on
279 health and tolerance between mouse groups separately and also the underlying
280 correlation between mean parasite load (x) and mean relative weight loss (y). We use
281 the terminology "coupling" (between resistance and tolerance) to describe
282 genotype-level correlation between tolerance and resistance additionally supported by
283 the absence of positive correlation between health-effect and resistance. Correlations
284 were tested using Spearman's rank correlation.

285 All analyses were performed using R version 3.5.2 (R Development Core Team,
286 2013)(negative binomial: function glm.nb from R package MASS (Venables & Ripley,
287 2002); ZIBN: function zeroinfl from R package pscl (Jackman, 2020; Zeileis et al.,
288 2008); linear model: function lm from R core package stats; mean and 95%
289 confidence intervals: function ggpredict from R package ggeffect (Lüdtke, 2018)).
290 Graphics were produced using the R package ggplot2 (Wickham, 2016) and compiled
291 using the free software inkscape (<https://inkscape.org>).

292 Results

293 1. General

294 Parasites of all isolates successfully infected all mouse groups (at the exception of 5
295 individuals infected by *E. falciformis* isolate Brandenburg88 that died or had to be
296 sacrificed due to a strong weight loss before the peak of shedding for this parasite),
297 meaning that no "qualitative infection resistance" (*sensu* Gandon and Michalakis
298 (2000)) was detected. For *E. ferrisi* (both isolates Brandenburg139 and
299 Brandenburg64), the pre-patent period was 5 days post infection (dpi) and the median
300 day of maximal oocyst shedding was 6 dpi (standard deviation sd=0.7 and 0.9,
301 respectively). The median day of maximum weight loss was 5 dpi for both isolates
302 (sd=2.1 and 1.7 respectively). For *E. falciformis* (isolate Brandenburg88) pre-patency
303 was 7 dpi, median day of maximal shedding was 8 dpi (sd=1.3) and median day of
304 maximal weight loss 9 dpi (sd=1.6)(**Figure 2**). Of note a considerable number of mice
305 infected with this isolate (13 out of 56 = 23%) died or had to be sacrificed at humane
306 end points less than 3 days after the oocysts shedding peak for the group, all
307 belonging to *M. m. musculus* subspecies (PWD, BUSNA, or their F1 PWDxBUSNA; 5
308 died at dpi 8, 5 at dpi 9, 3 at dpi 10). *E. falciformis* isolate Brandenburg88 was more
309 lethal for the *M. m. musculus* mice strains than for the other strains ($\chi^2_7 = 31.96$,
310 $P < 0.001$; **Table 2**).

311 2. No indication of host adaptation of *E. ferrisi*

312 We tested if our proxies for resistance, impact on weight and tolerance were different
313 between the four parental mouse strains and between both *E. ferrisi* infection isolates

(isolate Brandenburg64 and Brandenburg139). Maximum parasite load differed between mouse strains (LRT: $G=25.5$, $df=6$, $P<0.001$), but the interaction term mouse strain-parasite isolate was non significant (LRT: $G=4.1$, $df=3$, $P=0.25$). A similar result was found for maximum relative weight loss (LRT: mouse strain: $G=16.8$, $df=6$, $P=0.01$; interaction mouse strain-parasite isolate: $G=4.1$, $df=3$, $P=0.25$). This indicates that when resistance and impact on weight vary between host strains, they do so independently of the parasite isolate. Eventually, the variables mouse strain, parasite isolate and their interaction were found non significant at the 0.05 threshold for the slope of the linear regression between the two, indicating that differences of tolerance could not be detected between mouse strains or parasite isolates (**Figure 3**). Our results do not indicate either (1) an increased reproduction of each parasite in its matching host or (2) a higher tolerance of host infected by its matching parasite despite similar parasite reproductive output. Thus they do not support the hypothesis of host adaptation between *E. ferrisi* and its host.

3. Resistance and tolerance to *E. ferrisi* isolate Brandenburg64 are uncoupled

We tested coupling between resistance and tolerance for *E. ferrisi* isolate Brandenburg64 in our eight mouse groups. First, we tested whether our proxies for resistance, impact on weight and tolerance were different between the mouse groups. We found the maximum number of OPG and relative weight loss to be statistically different between mouse groups (LRT: maximum number of OPG: $G=26.6$, $df=7$, $P<0.001$; **Figure 4A**; maximum relative weight loss: $G=21.5$, $df=7$, $P<0.01$; **Figure 4B**). Tolerance was not found to significantly differ between mouse groups for this

337 parasite isolate (LRT: $G=6.8$, $df=7$, $P=0.45$; **Figure 4C**).

338 We found a non significant positive correlation between resistance (inverse of maximum
339 number of OPG) and impact on health (maximum weight loss) (Spearman's $\rho=0.69$,
340 $P=0.07$, $N=8$; **Figure 4D**). Eventually, we did not find a correlation between resistance
341 (inverse of maximum number of OPG) and tolerance (inverse of slope of maximum
342 weight loss on maximum OPG) (Spearman's $\rho=0$, $P=1$, $N=8$; **Figure 4E**).

343 In conclusion, we did not find indications of resistance-tolerance coupling for *E. ferrisi*
344 isolate Brandenburg64, the different mouse groups infected by this parasite presenting
345 a similar level of tolerance while showing an effect of quantitative resistance on health.

346 **4. Coupling between resistance and tolerance to *E. falciformis***

347 We then tested coupling between resistance and tolerance for *E. falciformis* isolate
348 Brandenburg88 in our eight mouse groups. First, we tested if our proxies for
349 resistance, impact on weight and tolerance were different between the mouse groups.
350 We found the maximum number of OPG and relative weight loss to be statistically
351 different between mouse groups (LRT: maximum number of OPG: $G=28.6$, $df=14$,
352 $P=0.012$; **Figure 5A**; maximum relative weight loss: $G=21$, $df=7$, $P<0.01$; **Figure 5B**).
353 Finally, contrary to our results on *E. ferrisi* isolate Brandenburg64, the tolerance
354 slopes for *E. falciformis* isolate Brandenburg88 were different between mouse groups
355 (LRT: $G=13.9$, $df=7$, $P=0.05$; **Figure 5C**).

356 We detected a strong negative correlation between (inverse of) resistance (maximum
357 number of OPG) and tolerance (inverse of slope of maximum weight loss on
358 maximum OPG) (Spearman's $\rho=-0.95$, $P=0.001$; **Figure 5E**). We conclude that this

correlation is unlikely a statistical artifact, as (1) mouse groups present statistically different values of resistance and tolerance and (2) we found a (non significant) negative correlation between resistance (inverse of maximum number of OPG) and impact on health (maximum weight loss) (Spearman's $\rho=-0.5$, $P=0.22$; **Figure 5D**), indicating that mouse groups losing more weight also shed less parasites.

We conclude that our results indicate the presence of negative resistance-tolerance coupling for *E. falciformis* isolate Brandenburg88.

Discussion

In this study, we assessed resistance and tolerance to two closely related parasites, *E. ferrisi* (two isolates) and *E. falciformis* (one isolate), in four mouse strains and their intra-and intersubspecific hybrids. Understanding this coupling has two major implications.

From a practical "measurement" perspective we can ask whether tolerance can be predicted from resistance, as the latter is easier to measure (e.g. in field sampling). Many studies assess the impact of parasites on host fitness based on resistance. If, as we found in the present study, resistance and tolerance are decoupled this can be misleading. In our host system, the house mice, for example, it has been shown that hybrids between *M. m. domesticus* and *M. m. musculus* are more resistant to parasites (Baird et al., 2012; Balard et al., 2020), including *Eimeria*, but tolerance could not be measured under natural conditions (Balard et al., 2020). The effect of parasites on host fitness in the evolution of the house mouse hybrid zone is thus still rather ambiguous (Baird & Goüy de Bellocq, 2019). We show that careful distinction between parasite

381 species is necessary when analysing parasite host interaction (see also Jarquín-Díaz
382 et al., 2019) and that it is indispensable to measure both resistance and tolerance in
383 *Eimeria* infections of house mice.

384 In this work we used the concept of tolerance as used originally in the plant literature
385 (Fineblum & Rausher, 1995) and later on transferred to animal studies
386 (Råberg et al., 2007). This concept of tolerance can be criticised, as it links
387 mathematically tolerance to resistance. Nevertheless, we argue that this view is
388 biologically meaningful considering resistance and tolerance as a step-wise defence
389 system, one step limiting the parasite multiplication, the other limiting the impact of
390 this multiplication on fitness-related traits. To limit the possible statistical artifact, our
391 approach did not only consist in calculating blindly correlations between resistance and
392 tolerance, but we also tested differences in resistance, impact on health and
393 tolerance. We additionally excluded the possibility of positive correlation between
394 mean health-effect and mean resistance of each host strains, which could indicate
395 some host strains having few parasites-few effects on health, and others more
396 parasites-more effects on health: this configuration would limit the possibility of
397 detecting an actual resistance-tolerance trade-off.

398 More generally, in an evolutionary perspective, coupling between resistance and
399 tolerance might help determine if coevolution between host and parasite can be
400 expected: a host-parasite system in which one finds negative coupling between
401 tolerance and resistance would be an especially promising system for studies of
402 host-parasite co-evolution. Indeed, coevolution in host-parasite systems is often
403 assumed but rarely proven (Woolhouse et al., 2002). Janzen (1980) notes that not all

404 parasite-host systems are coevolving. The presence of efficient host defences against
405 a given parasite is not necessarily produced in response to this parasite specifically
406 and the parasite does not necessarily respond specifically. In the mouse-*E. ferrisi*
407 system, where resistance and tolerance are decoupled, host and parasite fitness
408 might be decoupled as a result, making host-parasite coevolution less likely. In the
409 mouse-*E. falciformis* system we found a negative coupling between tolerance and
410 resistance, making coevolution between host and parasite more likely.

411 Differences between parasite species could explain the evolution of different
412 strategies: *E. ferrisi* commits to sexual reproduction after a relatively short time with
413 few cycles of asexual expansion (Al-khlifeh et al., 2019; Ankrom et al., 1975), while
414 *E. falciformis* has a relatively longer life cycle (Al-khlifeh et al., 2019; Haberkorn,
415 1970). As *E. ferrisi* infections do not reach extremely high intensities, high tolerance
416 might be the optimal strategy for both house mouse subspecies. Resistance could
417 then evolve relatively freely without any major impact of the parasite on the hosts'
418 health. Moreover, our results did not support host adaptation of *E. ferrisi*, which might
419 be explained by the absence of host-parasite coevolution caused by uncoupling of
420 parasite and host fitness. In the case of *E. falciformis*, the long life cycle might lead to
421 high tissue load. Tissue damage is observed during sexual reproduction for this
422 parasite (Ehret et al., 2017) and might mean that a certain level of resistance is
423 required. On the other hand, immunopathology has been observed in advanced
424 *E. falciformis* infections (Stange et al., 2012). These intrinsic characteristics of
425 *E. falciformis* might lead to multiple different optima for resistance and tolerance,
426 leading to a trade-off.

427 In conclusion, we argue that the difference between resistance and tolerance coupling
 428 in two different parasites can guide research in the house mouse system: if the effects
 429 of host hybridisation should be studied independently of potential host-parasite
 430 coadaptation, a parasite species leading to uncoupling between resistance and
 431 tolerance of the host (e.g. *E. ferrisi*) might be the most suitable parasite. If coevolution
 432 between hosts and parasites should be studied, a parasite species for which
 433 resistance and tolerance of the host are negatively correlated (e.g. *E. falciformis*)
 434 would be a more plausible target. Generally, we showed that the coupling between
 435 resistance and tolerance can differ between closely related parasite species and we
 436 argue that this trait of a host-parasite system determines the questions to be best
 437 approached with a particular parasite.

438 **References**

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582 Tables

Mouse		<i>Eimeria</i>		
group	subspecies	<i>E. ferrisi</i> Brandenburg139	<i>E. ferrisi</i> Brandenburg64	<i>E. falciformis</i> Brandenburg88
SCHUNT	<i>M.m.domesticus</i>	7 (5M / 2F)	14 (6M / 8F)	6 (3M / 3F)
STRA	<i>M.m.domesticus</i>	6 (2M / 4F)	15 (8M / 7F)	7 (4M / 3F)
SCHUNTxSTRA	<i>F1 M.m.domesticus</i>		6 (2M / 4F)	8 (5M / 3F)
STRAxBUSNA	<i>F1 hybrid</i>		8 (5M / 3F)	8 (3M / 5F)
SCHUNTxPWD	<i>F1 hybrid</i>		8 (3M / 5F)	6 (4M / 2F)
PWDxBUSNA	<i>F1 M.m.musculus</i>		9 (4M / 5F)	7 (4M / 3F)
BUSNA	<i>M.m.musculus</i>	6 (2M / 4F)	14 (8M / 6F)	7 (3M / 4F)
PWD	<i>M.m.musculus</i>	6 (3M / 3F)	13 (10M / 3F)	7 (1M / 6F)

Table 1. Infection experiment design.

Mouse		status at dpi 11	
subspecies	group	alive	dead
Mmd	SCHUNT	6	0
Mmd	STRA	7	0
Mmd	SCHUNTxSTRA	8	0
Mmd-Mmm	STRAxBUSNA	8	0
Mmd-Mmm	SCHUNTxPWD	6	0
Mmm	PWDxBUSNA	4	3
Mmm	BUSNA	3	4
Mmm	PWD	1	6
total		43	13

Table 2. Contingency table: number of mice and status at dpi 11 for each mouse group upon infection with *E. falciformis* isolate Brandenburg88.

583 Figures legends

584 **Figure 1. Parasite isolates and mouse wild-derived strains.** (A) Map showing
585 locations at which mice were collected for breeding of mouse strains and isolation of
586 parasites. The purple line is an estimation of the center of the house mouse hybrid
587 zone between *M. m. domesticus* and *M. m. musculus* based on sampling and
588 genotyping of mice in this area (Balard et al., 2020; Ďureje et al., 2012; Macholán
589 et al., 2019). (B) The eight mouse groups (parents and F1s) used in our experimental
590 infections.

591 **Figure 2. Parasite density (A) and relative weight (B) during *Eimeria* infection.**
592 Parasite density is calculated as number of oocysts detected (in millions) per gram of
593 feces, relative weight is calculated as the percentage of weight compared to day 0.
594 Mean and 95% CI are plotted for each parasite isolate. All mouse groups are pooled

595 together.

596 **Figure 3. Comparison of resistance, impact on weight and tolerance between**
597 **mouse strains for both *Eimeria ferrisi* isolates.** (A) Maximum oocysts per gram of
598 feces used as a proxy for (inverse of) resistance; (B) Impact on host health measured
599 as the maximum weight loss during patent period relative to starting weight (%); (C)
600 Tolerance estimated by the slope of the linear regression with null intercept modelling
601 maximum relative weight loss as a response of maximum oocysts per gram of feces. A
602 steep slope corresponds to a low tolerance. We did not detect (A) either higher parasite
603 shedding of the Eastern parasite isolate in Eastern mouse strains and vice versa or (C)
604 higher tolerance of Eastern hosts infected by Eastern parasite isolate and vice versa,
605 thus our results do not support the hypothesis of local adaptation between *E. ferrisi* and
606 its host.

607 **Figure 4. No indication of resistance-tolerance coupling for *E. ferrisi* isolate**
608 **Brandenburg⁶⁴.** Colors represent mouse subspecies (blue: *M. m. domesticus*, red:
609 *M. m. musculus*, purple: Mmd-Mmm). Left side: comparison of maximum oocysts per
610 gram of feces used as a proxy for (inverse of) resistance (A), impact on weight
611 measured as the maximum weight loss during patent period relative to starting weight
612 (B) and tolerance between mouse groups estimated by the slope of the linear
613 regression with null intercept modelling maximum relative weight loss as a response
614 of maximum oocysts per gram of feces, a steep slope corresponding to a low
615 tolerance (C). Maximum number of OPG and relative weight loss differ between
616 mouse groups, but tolerance is similar. Right side: non significant positive correlation
617 between mean maximum oocysts per gram of feces and mean relative weight loss (D)

618 and absence of correlation between maximum oocysts per gram of feces used as a
619 proxy for (inverse of) resistance and tolerance (E); Grey error bars represent 95%
620 confidence intervals. Our results do not support coupling between resistance and
621 tolerance *E. ferrisi* isolate Brandenburg64.

622 **Figure 5. Coupling between resistance and tolerance for *E. falciformis* isolate**
623 **Brandenburg88.** Colors represent mouse subspecies (blue: *M. m. domesticus*, red:
624 *M. m. musculus*, purple: Mmd-Mmm). Left side: comparison of maximum oocysts per
625 gram of feces used as a proxy for (inverse of) resistance (A), impact on weight
626 measured as the maximum weight loss during patent period relative to starting weight
627 (B) and tolerance between mouse groups estimated by the slope of the linear
628 regression with null intercept modelling maximum relative weight loss as a response
629 of maximum oocysts per gram of feces, a steep slope corresponding to a low
630 tolerance (C). Maximum number of OPG, relative weight loss and tolerance differ
631 between mouse groups. Right side: non significant negative correlation between
632 mean maximum oocysts per gram of feces and mean relative weight loss (D) and
633 strong negative correlation between maximum oocysts per gram of feces used as a
634 proxy for (inverse of) resistance and tolerance (E); Grey error bars represent 95%
635 confidence intervals. Our results support coupling between resistance and tolerance
636 *E. falciformis* isolate Brandenburg88.

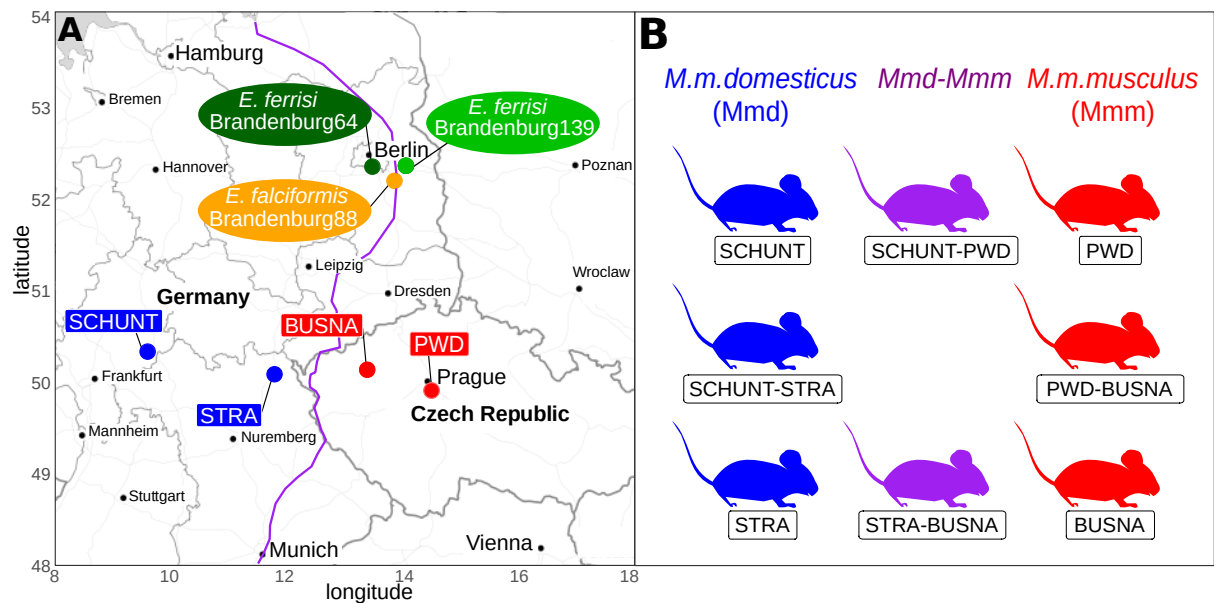


Figure 1: Parasite isolates and mouse wild-derived strains.

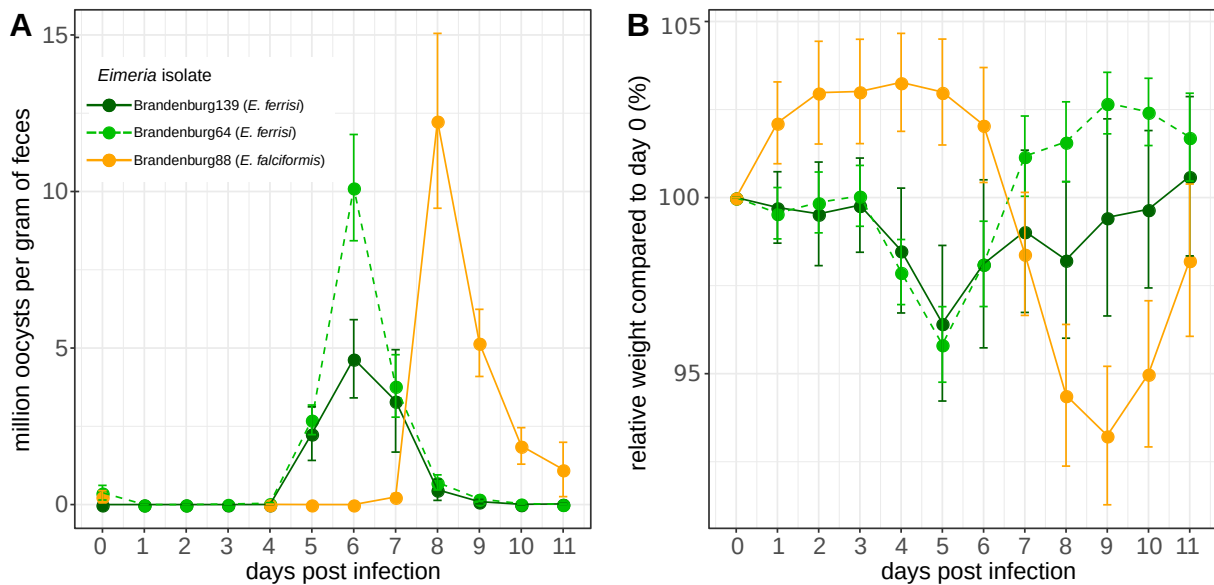


Figure 2: Parasite density (A) and relative weight (B) during *Eimeria* infection.

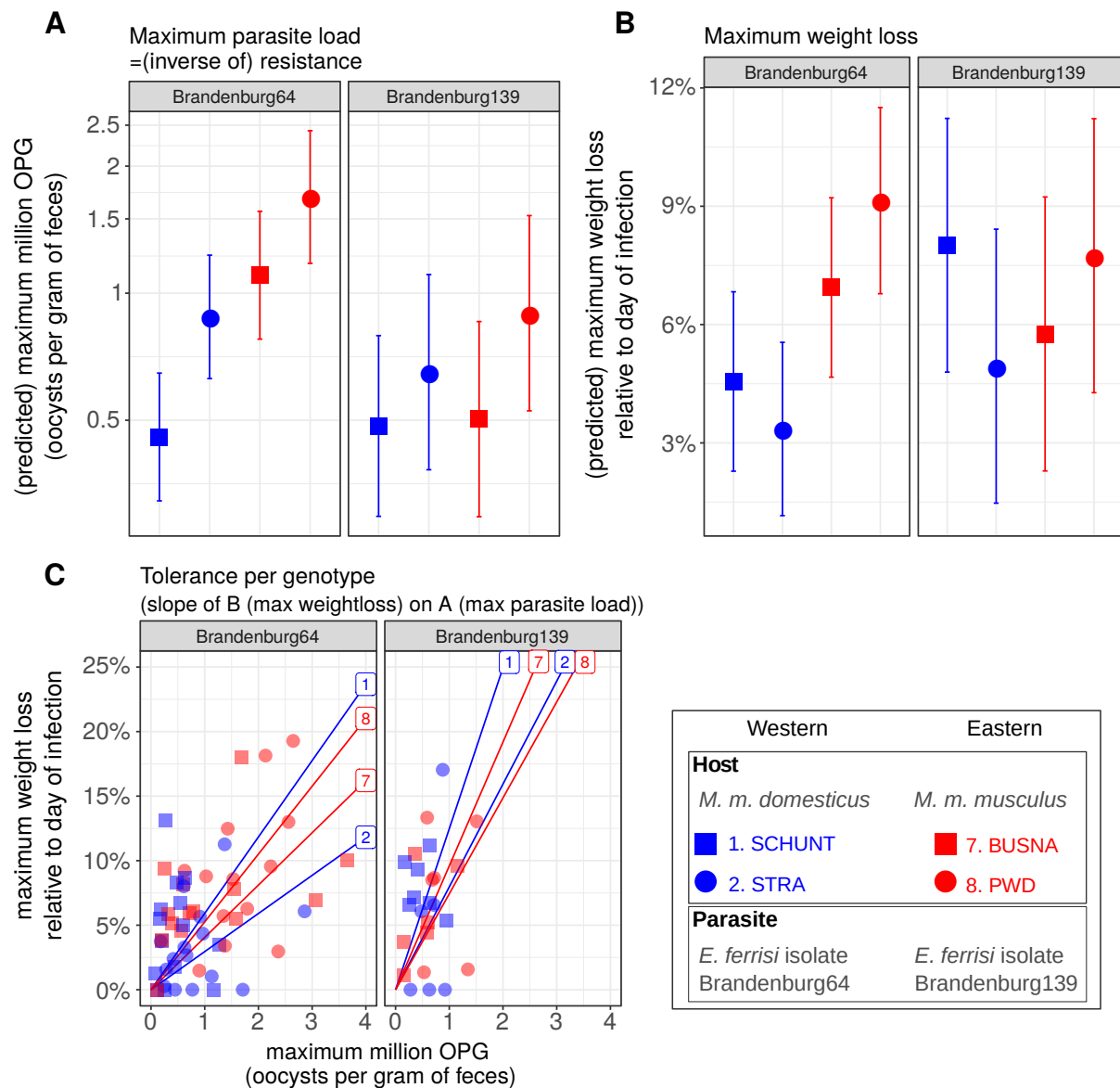


Figure 3: Comparison of resistance, impact on weight and tolerance between mouse strains for both *Eimeria ferrisi* isolates.

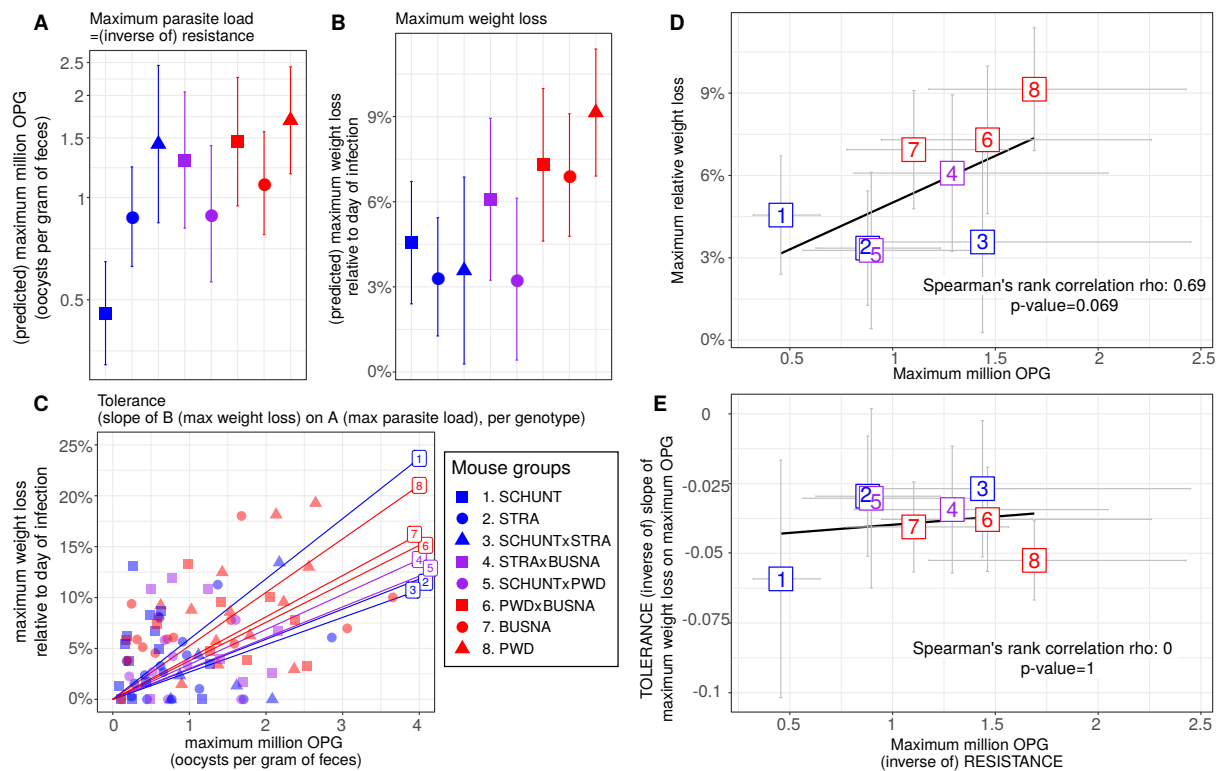


Figure 4: No indication of resistance-tolerance coupling for *E. ferrisi* isolate Brandenburg64.

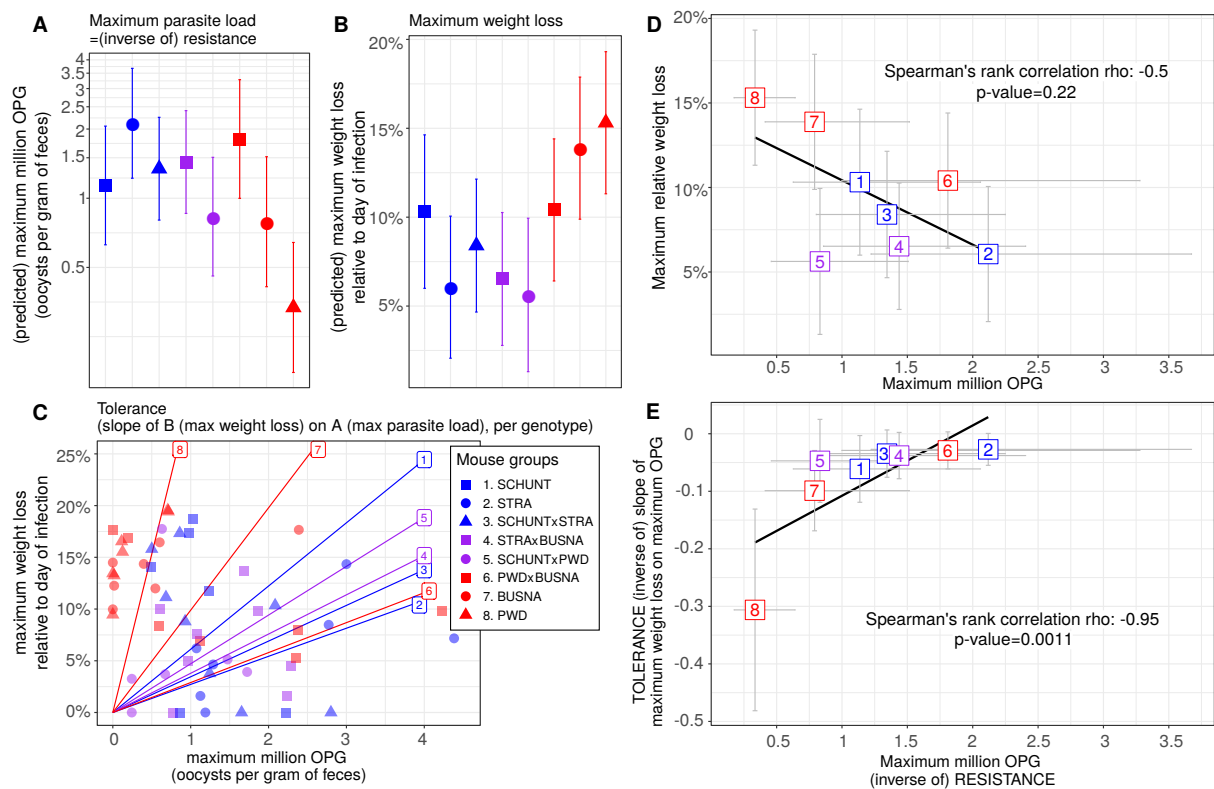


Figure 5: Coupling between resistance and tolerance for *E. falciformis* isolate Brandenburg88.