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Title:

Shifting effects of host physiological condition following pathogen establishment

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19 **Abstract:**

20

21 Understanding host persistence with emerging pathogens is essential for conserving populations.
22 Hosts may initially survive pathogen invasions through pre-adaptive mechanisms. However,
23 whether pre-adaptive traits are directionally selected to increase in frequency depends on the
24 heritability and environmental dependence of the trait and the costs of trait maintenance. Body
25 condition is likely an important pre-adaptive mechanism aiding in host survival, although can be
26 seasonally variable in wildlife hosts. We used data collected over seven years on bat body mass,
27 infection, and survival to determine the role of host body condition during the invasion and
28 establishment of the emerging disease, white-nose syndrome. We found that when the pathogen
29 first invaded, bats with higher body mass were more likely to survive, but this effect dissipated
30 following the initial epizootic. We also found that heavier bats lost more weight overwinter, but
31 fat budgeting depended on infection severity. Lastly, we found little support that bat mass
32 increased in the population after pathogen arrival, and there was high annual plasticity in
33 individual bat masses. Overall, our results suggest that factors that contribute to host survival
34 during pathogen invasion may diminish over time, and are potentially replaced by other host
35 adaptations.

36

37 **Keywords:** body mass, emerging infectious disease, wildlife disease, population impacts, white-
38 nose syndrome, *Pseudogymnoascus destructans*, disease ecology, host physiology, body
39 condition

40 **Introduction:**

41

42 The introduction of novel pathogens to naive hosts can have profound effects on
43 populations [1-7]. Hosts may survive initial pathogen invasion through multiple mechanisms
44 including evading infection or pre-adaptive traits that allow for survival despite infection or
45 disease [8, 9]. Importantly, factors enabling hosts to survive during initial invasion may not
46 confer any advantage subsequently, particularly if pre-adaptive traits have strong tradeoffs, or are
47 highly plastic (e.g. environmentally dependent) [10, 11]. Ultimately, traits that determine long-
48 term host-pathogen coexistence may take longer to evolve and become widespread than traits
49 allowing for initial survival, particularly if such traits provide stronger protection than pre-
50 adaptive mechanisms [10, 12-14].

51 Factors that affect the probability of host survival with invasive pathogens include age,
52 chronic disease, prior exposure, and body mass [15]. In general, hosts with adequate fat stores,
53 high nutrient levels, and access to high quality habitat should demonstrate improved disease
54 outcomes over weaker hosts. However, host body condition can be highly variable across
55 seasons and years, even within individuals, leading to heterogeneity in the relationship between
56 host body condition and disease, and making it a less reliable mechanism long-term [16].
57 Variable effects of body condition may be particularly pronounced when there is highly seasonal
58 availability of food sources, leading to high stochasticity among individuals in their ability to
59 consistently maintain high body condition when faced with annual disease outbreaks.

60 White-nose syndrome (WNS) is a seasonal annual epizootic of bats caused by the fungal
61 pathogen *Pseudogymnoascus destructans* [17-20]. White-nose syndrome was first detected New
62 York, USA in 2006, and has caused widespread declines in hibernating bat populations across
63 North America [6, 21, 22]. *Pseudogymnoascus destructans* grows optimally in cool conditions
64 (1–17 °C) [23], resulting in annual winter epidemics that occur when bats begin hibernating [18].
65 Invasion of *P. destructans* into bat skin tissue causes severe physiological disruption, elevating
66 bat metabolic rate and increasing respiratory acidosis [24, 25]. Bats, in turn, arouse to normalize
67 blood pH which further increases evaporative water loss and causes dehydration. Higher energy
68 expenditure from infection, increases fat loss, and emaciation, which frequently leads to
69 mortality [26-28].

70 Increases in stored fat and improved budgeting of fat overwinter are therefore
71 hypothesized to be important mechanisms determining bat survival with WNS [29-31], which
72 typically increases within 4-5 years of WNS arrival after initially severe declines [6, 17, 32, 33].
73 However, other mechanisms of host persistence have also been described, including potential
74 increases in host resistance through immunity or microbially-mediated reductions in pathogen
75 growth [17, 33], and movement toward colder roosting conditions which limits fungal growth
76 [34, 35]. Nonetheless, changes in body mass have the potential to have strong effects on bat
77 survival, but comprehensive analyses on the effect of body mass on individual bat survival with
78 WNS in the field have yet to be conducted. In addition, because host body condition may exhibit
79 high annual variability [36], the importance of body mass as a sustained factor affecting
80 population persistence with WNS merits additional investigation. Here, we investigate changes
81 in the effect of body mass on survival of individual little brown bats (*Myotis lucifugus*) during
82 the invasion and establishment of *P. destructans* across 24 sites. We hypothesized that while
83 fatter bats might initially exhibit higher survival, the positive effects of higher body condition
84 could diminish over time as host disease resistance increases in bat populations.

85

86 **Methods:**

87 We studied the arrival and establishment of *P. destructans* at 24 hibernacula (caves and
88 mines where bats spend the winter) in Virginia, Wisconsin, Illinois, and Michigan over seven
89 years (Tables S1-S3). We visited sites twice per winter and collected data on infection status and
90 body mass of bats. At each site, we sampled up to 25 individual bats stratified across site
91 sections. Because sites used in this study were primarily small mines where it was possible to
92 observe all bats present, in many instances, all individuals in the population were sampled. For
93 each bat, we collected a standardized epidermal swab sample [18], attached a unique aluminum
94 band, and measured body mass using a digital scale (GDealer, accuracy +/- 0.03 grams). Because
95 common condition indices are no more effective than body mass for estimating fat stores [37],
96 we did not include information on bat forearm size in order to reduce handling disturbance. At
97 every visit, we recorded and resampled any previously banded bats present. We stored swabs in
98 RNAlater until processing. We tested samples for *P. destructans* DNA using real-time PCR and
99 quantified fungal loads [21, 38]. Animal handling protocols were approved by Virginia Tech
100 IACUC (#17-180, #20-150).

101 We investigated the effect of bat early hibernation (November) body mass on the
102 probability an individual was recaptured overwinter using a generalized linear mixed model
103 (GLMM) with a binomial distribution and a probit link, with site as a random effect, and body
104 mass and disease phase (epidemic = 1- 3 years since pathogen arrival, or established = 4-7 years
105 since pathogen arrival) as interacting fixed effects. Phases were established based on previous
106 results demonstrating that populations approach stability by year 4 following WNS arrival [6, 32]
107 For analyses of individual survival and body mass, results were similar whether we used
108 categorical disease phase or years since WNS as a continuous variable (Appendix) and grouping
109 by phase maximized the number of bats in the epidemic years when mortality was high and the
110 number of recaptured bats was low. For bats that were recaptured overwinter, we examined the
111 effect of early winter body mass and infection on the amount of mass lost overwinter during both
112 the epidemic and established phase using a linear mixed model with site as a random effect and
113 the change in body mass as the response variable and fixed effects of early winter mass
114 interacting early winter fungal loads with additional additive effect of disease phase. Finally, we
115 explored changes in mass over time since the invasion of *P. destructans* on an individual and
116 population level to examine both plasticity and phenotypic change. For bats that were recaptured
117 in multiple years, we used a linear mixed model with mass as a response variable, years since
118 WNS as a fixed effect, and bat band ID as a random effect to explore plasticity in whether
119 individual bat mass changed over time. At a population level, declines in sites with the best
120 invasion mass data limited our ability to explore changes in mass, so we restricted our analyses
121 to N=5 sites that were measured during invasion and had sufficient bats to estimate during
122 established periods using \log_{10} mass as our response variable (logged to normalize) and years
123 since WNS interacting with season with site as a random effect.

124

125 **Results:**

126

127 As WNS invaded and caused massive declines in bat populations, bats that were heavier
128 in early winter were more likely to be recaptured than lighter ones (Fig. 1; slope of mass \pm SE:
129 0.320 ± 0.14 , $P = 0.0220$). However, after WNS established in sites (years 4-7 following *P.*
130 *destructans* detection), recapture overall was higher than during the epidemic (invasion vs
131 establishment coef: 3.551 ± 1.46 , $P = 0.0152$), and the effect of mass on the probability of

132 recapture was significantly lower than the epidemic phase (interaction slope: -0.357 ± 0.16 , $P =$
133 0.0250), and the slope did not differ significantly from 0 (Appendix 1.0.3).

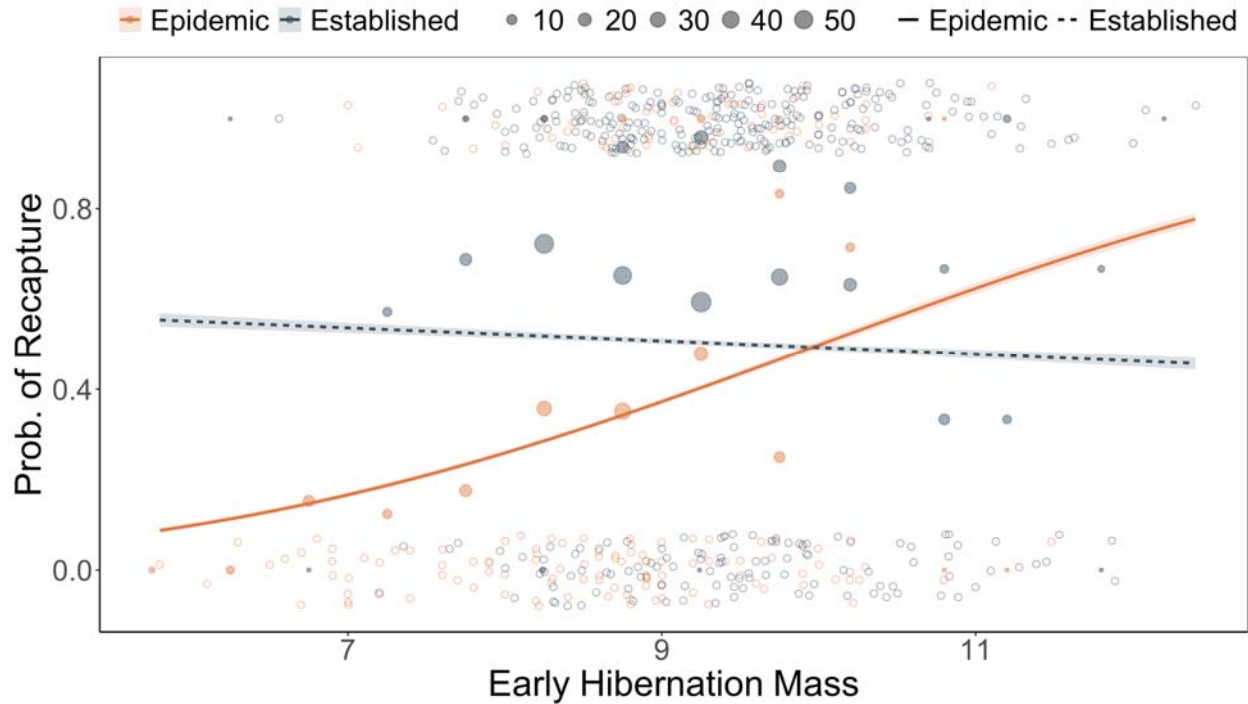
134 For bats that survived overwinter and were recaptured, mass lost overwinter depended on
135 both early hibernation weight and infection, and their interaction (Fig. 2A; $P = 0.00948$). There
136 was little support for including disease phase as a predictor ($P = 0.27$), likely due to the paucity
137 of bats recaptured during the epidemic phase when mortality was high (Table S2). Generally,
138 bats that were heavier lost more weight overwinter than bats that were lighter (coef: $-0.737 \pm$
139 0.16 , $t = -4.613$). In addition, as infection increased, so did the amount of mass lost (coef: 1.002
140 ± 0.41 , $t = 2.467$), but only for bats that were heavier in early winter; lighter bats lost less weight
141 and weight loss did not vary with higher fungal loads (early mass:early loads coef: $-0.106 \pm$
142 0.04 , $t = -2.594$, Appendix 2.0.2).

143 We found limited support for increases in mass at a population-level. Including years
144 since pathogen arrival as a continuous effect, we found no clear support for increases in mass at a
145 population-level (years since pathogen invasion coef: 0.002 ± 0.002 , $t = 0.983$, Fig. 2B, Table S3,
146 Appendix 3.0.2). We did find support for a modest increase in \log_{10} early hibernation body mass
147 between the epidemic and established periods at 5 sites that were sampled at all time points in
148 most years (established coef: 0.011 ± 0.005 , $t = 2.031$, Fig. S1, Appendix 3.0.4), however this was
149 largely due to an increase between one annual time step (Year 3 to Year 4). We found no support
150 for an increase in mass due to plasticity (Appendix 4). Using just recaptured bats, we found weak
151 and unclear support for increases in \log_{10} early hibernation body mass with years since WNS
152 establishment (0.0037 ± 0.003 , $t = 1.508$, Fig. S1 closed circles, Table S2, Appendix 4.0.2).
153 Furthermore, masses of individual bats that were recaptured in multiple years decreased non-
154 significantly (-0.0023 ± 0.003 , $t = -0.701$, Fig. S2, Appendix 4.03). Among individual bats
155 recaptured annually, there was high plasticity in body mass which ranged from $-1.78 : +1.09$ g,
156 suggesting that bat fat stores may be highly dependent on local conditions in summer and
157 autumn.

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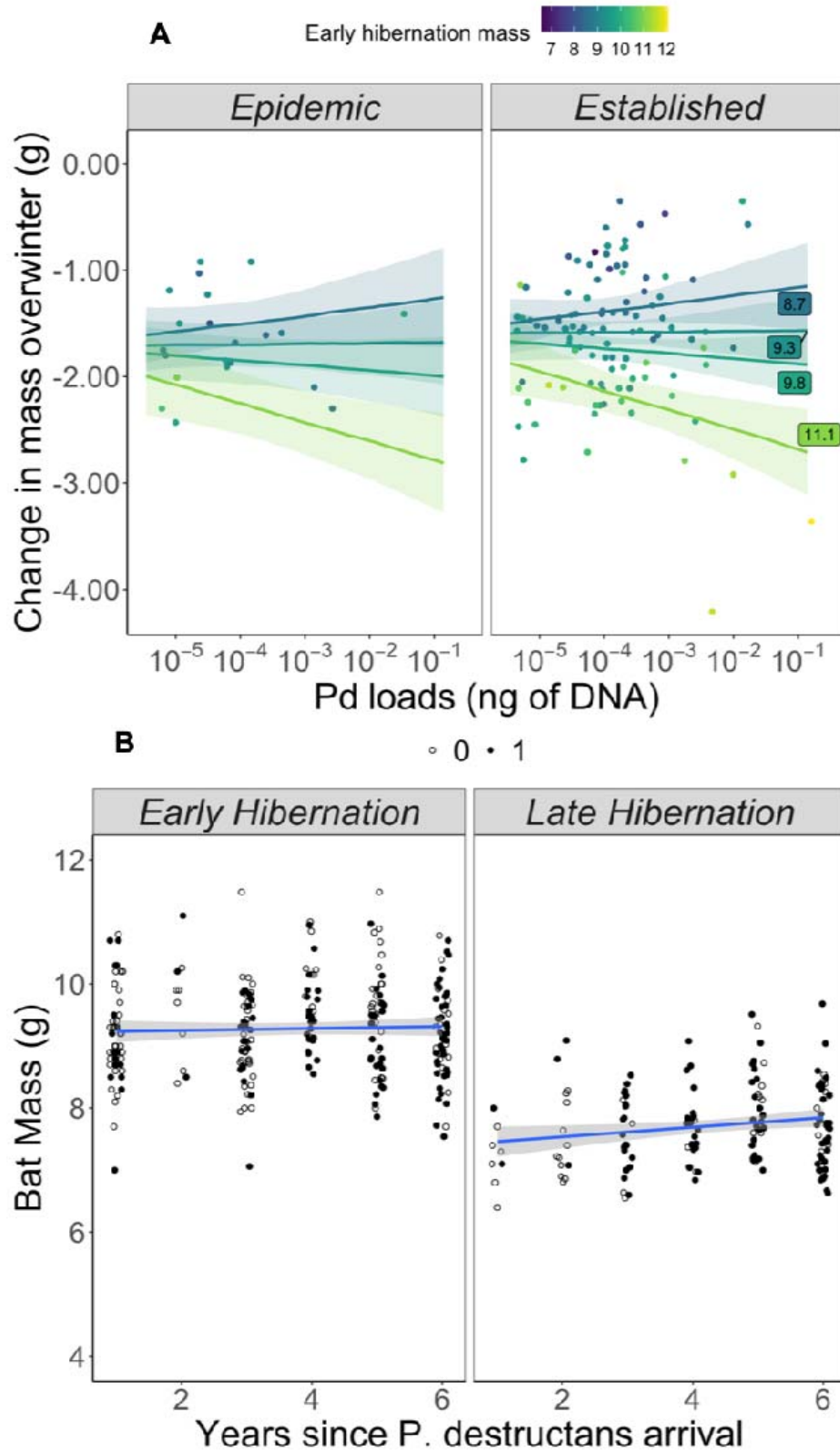
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162 Figure 1. The effects of body mass during early hibernation on the probability of little brown bat
163 recapture vary with time since *P. destructans* arrival. In years 0–3 post *P. destructans* arrival, the
164 probability a bat was recaptured overwinter increased as early hibernation mass increased.
165 However, after WNS established (>3 years since *P. destructans* arrival), there was no longer a
166 clear trend between early hibernation body mass and bat survival. Solid points of early
167 hibernation body masses during each phase show the fraction recaptured at 0.5 g bins (e.g. 9.75-
168 10.25) and sample sizes for binned data.



169

170 Figure 2. (A) Fungal loads and early hibernation (November) body mass of little brown bats

171 strongly influences the change in individual bat mass over winter. Points show individual bats

172 captured in both early and late hibernation. Colors denote masses of bats during early hibernation
173 and labeled lines show predictions based on the 25th (8.7 g), 50th (9.3 g), 85th (9.8 g), and 95th
174 (11.1 g) percentiles of the early hibernation masses. Bats that have higher initial body mass lose
175 more weight over winter than bats with lower body mass (i.e. darker lines are higher), suggesting
176 that bats budget fat stores accordingly over winter. In addition, fungal loads significantly modify
177 the effect of early hibernation mass on mass lost overwinter. Bats with high infections that were
178 heavier lose more mass than similarly infected bats that were lighter, suggesting that highly
179 infected bats that survive to be recaptured budget fat in accordance with their infection status.
180 **(B)** Average body mass of banded little brown bats in early (November) and late (March) that
181 were recaptured (filled circles) or not recaptured (open circles) overwinter during the WNS
182 epidemic (Years 0-3) and WNS established period (Years 4+) at the same sites over time (N=5).
183 We found no clear support that hibernation body masses of bats increased over time when
184 examining these data continuously (top) but marginal support categorically (Fig S1).

185

186 **Discussion**

187

188 We found that the effect of body mass on survival waned as the epidemic progressed.
189 Furthermore, fat loss in bats increased with initial stored fat, as has been previously found in
190 another species [39], suggesting that bats surviving with disease are budgeting fat stores to
191 mitigate the physiological disruption posed by WNS. Importantly, we did not find evidence that
192 bat survival once the disease established was enhanced by increases in the amount of stored fat
193 [29]. We also found little support that fat increased at the population level as the disease
194 established. When treating years since pathogen arrival continuously, there was no clear trend of
195 increases in fat at the population-level. In some years, annual increases in fat occurred, but these
196 were modest relative to the range of body conditions at the start of hibernation (recaptured bats
197 during the established WNS period ranged from 7-12 grams and gains were an average of 0.18
198 grams. We also found no support of consistent mass increases in individual bats, and year to year
199 fat stores were highly variable (range -1.78: +1.09 grams).

200 There are several potential reasons that could explain why the importance of fat changed
201 as *P. destructans* established. First, the initial epizootic may have selected for fatter individuals,
202 thus making the effects of fat less apparent as the pathogen established. However, body mass

203 differences between the invasion and established phases were very modest relative to annual
204 plasticity in bat masses, suggesting that this is unlikely. Second, bats in some populations have
205 evolved higher pathogen resistance [33, 35] which may have reduced selection for increased
206 body mass, particularly if fatter bats face other tradeoffs, such as reduced flight abilities [40, 41].
207 Third, bats have shifted to using cooler microclimates that also reduce the growth of the fungus,
208 resulting in less severe disease [34]. Fourth, changes in the pathogen (e.g. a reduction in
209 virulence) could have enabled more hosts to survive, thus experiencing fewer adverse effects
210 (e.g. excess fat loss) from the pathogen [42, 43]. Lastly, bats may have adapted to the
211 physiological disruption posed by infection, as evidenced by the relationship between mass loss,
212 infection, and early hibernation weight. This finding is consistent with the hibernation
213 optimization hypothesis [44-46], suggesting that bats do not use a fixed amount of fat during
214 hibernation [47, 48], and generally aligns with findings conducted on unaffected little brown bats
215 that demonstrated increases in arousals with increases in early hibernation fat [44]. Overall,
216 increased fat stores may have been beneficial initially, but changes in other host or pathogen
217 traits may have relaxed selection on fat over time.

218 Our results have important implications for the conservation of bats impacted by WNS.
219 Supplemental feeding and enhancement of autumn bat habitat to increase insect prey abundance
220 have been explored as a management strategy to increase bat fat stores to reduce WNS impacts
221 [49]. Our results strongly suggest that while this may have been effective prior to or during
222 pathogen invasion, it provides little benefit to bats once the pathogen has been established for
223 several years. We find that bats budget fat in accordance with their infection severity and initial
224 fat stores, suggesting that supplemental feeding might not achieve the desired benefit of
225 enhancing bat survival if bats simply alter fat use accordingly. In addition, supplemental feeding
226 of wildlife may have unexpected negative consequences, including increases in predation,
227 increases in susceptibility due to less nutritious food sources, and enhancement of pathogen
228 spread due to host aggregation [50], and these potential negative effects should be carefully
229 considered before widescale implementation.

230 Species survival in the face of global change will likely require rapid adaptation and
231 change itself may outpace the speed at which species can evolve [51, 52]. For species and
232 populations that persist, some traits that may be beneficial for initial survival may prove less
233 important over time [9, 53]. This phenomenon may be partly explained by coevolutionary theory

234 which suggests that both hosts and pathogen must constantly adapt and innovate in order to
235 maintain high fitness [12]. Ultimately, developing a more comprehensive understanding of the
236 pre-adaptive factors that aid in population health can enable us to build more resilient
237 populations in the Anthropocene.

238

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241 the many landowners for site access.

242

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246

247 **Data Availability Statement**

248 The datasets and code generated in this study have been included in the electronic supplementary
249 material for review and will be deposited in Dryad Digital Repository upon final submission.

250 Exact site locations are not disclosed to protect endangered species and landowners.

251

252 **Ethics Statement**

253 Animal handling protocols were approved by Virginia Tech IACUC (#17-180, #20-150). Field
254 work was conducted under approved permits from the Wisconsin Department of Natural
255 Resources, the Virginia Division of Game and Inland Fisheries, the Illinois Department of
256 Natural Resources, and the Michigan Department of Natural Resources. All personnel followed
257 field hygiene protocols for *P. destructans* as recommended by the USFWS.

258

259 **Conflict of Interest**

260 We declare no competing interests.

261

262 **Author Contributions**

263 K.E.L.: conceptualization, investigation, methodology, funding acquisition, resources, project
264 administration, data curation, formal analysis, writing-original draft, writing-review and editing;

265 M.J.K.: investigation, methodology, writing-review and editing,

266 N.A.L.: investigation, methodology, writing-review and editing,
267 J.P.W.: investigation, writing-review and editing,
268 H.M.K.: investigation, writing-review and editing,
269 J.A.R.: investigation, writing-review and editing,
270 J.E.D.: investigation, resources
271 K.L.P.: investigation, writing-review and editing,
272 J.T.F.: investigation, funding acquisition, writing-review and editing,
273 A.M.K.: investigation, funding acquisition, writing-review and editing,
274 J.R.H.: conceptualization, investigation, methodology, funding acquisition, resources, project
275 administration, data curation, writing-review and editing
276

277

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