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1 Survival rate and breeding outputs in a high Arctic seabird exposed to legacy
2 persistent organic pollutants and mercury

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26

27 **Abstract**

28 Chronic exposure to pollutants may represent a threat for wildlife. We tested whether adult
29 survival rate, breeding probability and breeding success the year of sampling and the
30 following year were affected by blood levels of mercury or persistent organic pollutants in
31 Svalbard black-legged kittiwake *Rissa tridactyla*, by using capture–mark–recapture models
32 over a five-year period. Survival rate was negatively linked to HCB levels in females, to
33 chlordane mixture and oxychlordane, tended to decrease with increasing PCBs or DDE levels,
34 but was unrelated to mercury. Breeding probability decreased with increasing mercury levels
35 during the sampling year and with increasing CHL or HCB levels during the following year,
36 especially in males observed as breeders. Surprisingly, the probability of raising two chicks
37 increased with increasing HCB levels. Although levels of these legacy pollutants are expected
38 to decline, they represent a potential threat for adult survival rate and breeding probability,
39 possibly affecting kittiwake population dynamics.

40

41 **Capsule abstract:** Negative effects of pollutants were detected on future breeding
42 probabilities and on adult survival rate in a High Arctic seabird species.

43

44 **Keywords:** heavy metals, kittiwake, population, pesticides, PCBs

45

46 **1. Introduction**

47 Contaminants, such as mercury (Hg) and persistent organic pollutants (hereafter
48 POPs) may represent a threat for wildlife, because of their detrimental effects on
49 developmental, neurological, physiological, endocrine and immune functions (Barron et al.,
50 1995; Bustnes et al., 2003a; Tan et al., 2009; Letcher et al., 2010). Despite a growing
51 environmental concern during the last decades, the demographic consequences of pollution
52 remain poorly evaluated in free-living vertebrates. Only a few long-term monitoring studies
53 have addressed the consequences of environmental pollutants on survival rate and long-term
54 reproductive outputs. Hg or POP levels were negatively related to long-term breeding
55 probability and success in the wandering albatross *Diomedea exulans* and in two *Catharacta*
56 *skua* species (Goutte et al., 2014a,b). Apparent survival rate was lower in glaucous gulls
57 *Larus hyperboreus*, bearing the highest levels of oxychlordan, a metabolite of the chlordane
58 mixture, which is regarded as one of the most toxic POPs (Erikstad et al., 2013). However,
59 adult survival rate was not related to POPs or Hg in tree swallows (*Tachycineta bicolor*), king
60 eiders (*Somateria spectabilis*), white-winged scoters (*Melanitta fusca*), wandering albatrosses
61 and two *Catharacta skua* species (Wayland et al., 2008; Hallinger et al., 2011; Goutte et al.
62 2014a,b).

63 Some seabird species appear as ideal models for assessing the demographic
64 consequences of environmental pollution. Firstly, individual detection probabilities of
65 seabirds at breeding colonies are generally high because of high overall site fidelity (e.g.
66 Gauthier et al., 2012). Secondly, large sample sizes and accurate measures of breeding outputs
67 are relatively easy to obtain in seabird's colonies. Thirdly, these long-lived top predators are
68 particularly exposed to contaminants, because of bioaccumulation process and
69 biomagnification along the trophic web (Rowe, 2008; Letcher et al., 2010).

70 The present study focusses on black-legged kittiwakes *Rissa tridactyla* breeding in
71 Svalbard, a Norwegian archipelago in the north-western part of the Barents Sea. The
72 Norwegian Arctic is recognized as a final sink for organic and metallic pollutants, which are
73 transported by atmospheric and oceanic currents and by large rivers (Gabrielsen and
74 Henriksen, 2001). Previous studies in this population of Svalbard kittiwakes have reported
75 deleterious effects of Hg and POPs on endocrine mechanisms (Nordstad et al., 2012; Tartu et
76 al., 2013, 2014). The estimated number of breeding pairs in the Svalbard archipelago is
77 270 000 in 215 colonies (Strøm, 2006). The status of black-legged kittiwakes is near
78 threatened, with a pronounced population decline from 1995 to 2002 and a slight increase
79 from 2002 to 2012 (Barrett et al., 2012). This study aims at detecting whether breeding
80 probability the year of sampling and demographic traits the following year (apparent adult
81 survival rate, breeding probability, probability of successfully raising at least one chick and
82 probability of successfully raising two chicks) were correlated with individual blood levels of
83 Hg or POPs. According to the few available long-term studies on polar seabird species
84 (Erikstad et al., 2013; Goutte et al., 2014a,b), we predicted deleterious effects of Hg or POPs
85 on breeding probability and breeding success during the year of sampling and during the
86 following year and deleterious effects of the chlordane mixture and metabolites on survival
87 rate in black legged kittiwakes.

88

89 **2. Materials and methods**

90 *2.1. Study area and birds*

91 Our study was conducted in a colony of black legged kittiwakes at Kongsfjorden,
92 Svalbard (78°54'N, 12°13'E), seven kilometers southeast of Ny-Ålesund, Norway. Kittiwakes
93 are colonial seabirds that breed on cliffs throughout the northern parts of the Pacific and

94 Atlantic, including the Barents Sea region up to the Svalbard Archipelago (Anker-Nilssen et
95 al., 2000). Kittiwakes were studied in one plot of around 150 pairs breeding on cliff ledges at
96 heights of 5–10 m. Male and female kittiwakes were sampled once, between 2007 to 2010
97 years, during the pre-laying stage (arrival, nest building, courtship and mating period) from
98 23rd of April to 16th of June. Table 1 summarizes sampling information: a total of 105
99 kittiwakes were sampled for measurement of Hg and 138 kittiwakes for POPs. We chose to
100 focus our study on the pre-laying period, because sampling kittiwakes during the incubating
101 or chick-rearing period would have biased our demographic study towards good-quality birds
102 (breeders) and would have missed possible effects in non-breeders.

103

104 *2.2. Capture and blood sampling*

105 Male and female kittiwakes were caught on the nests with a noose at the end of a 5 m
106 fishing rod. Blood samples were collected from the alar vein with a 2 ml heparinized syringe
107 and a 23-gauge needle. Kittiwakes were individually marked with metal rings and PVC
108 plastic bands engraved with a three-digit code and fixed to the bird's tarsus for identification
109 from a distance without perturbation.

110

111 *2.3. Laboratory analyses*

112 Blood samples were centrifuged. Plasma and red blood cells were separated and stored
113 at – 20°C. Molecular sexing was performed on red blood cells as detailed in Weimerskirch et
114 al. (2005). Total Hg was measured at the laboratory Littoral Environnement et Sociétés
115 (LIENSs) from lyophilized red blood cells with an Advanced Mercury Analyzer
116 spectrophotometer (Altec AMA 254). At least two aliquots ranging from 5 to 10 mg dry
117 weight were analyzed for each individual until having a relative standard deviation <5 %. As
118 described by Bustamante et al. (2006), accuracy was checked using a certified reference

119 material (CRM, Tort-2 Lobster Hepatopancreas, NRC, Canada; certified Hg concentration:
120 $0.27 \pm 0.06 \mu\text{g g}^{-1}$ dry mass; with recoveries of 98 to 102%). Mass of CRM was adjusted to
121 represent the same amount of Hg introduced in the AMA compared to that in blood samples.
122 Blanks were analysed at the beginning of each set of samples and the detection limit of the
123 method was $0.005 \mu\text{g g}^{-1}$ dry mass. Mean values of replicates were used in statistical
124 analyses.

125 POPs were analysed from whole blood samples at the Norwegian Institute for Air
126 Research (NILU) in Tromsø. The following compounds were analysed: polychlorinated
127 biphenyl (CB, -99, -118, -138, -153, -180, -183 and -187) hereafter referred as Σ PCBs, p,p'-
128 DDE (p,p'-dichlorodiphenyldichloroethylene, HCB (hexachlorobenzene), and the chlordane
129 mixture (trans-chlordane, trans-, cis-nonachlor) and metabolites (oxychlordane), hereafter
130 referred as CHL. To a blood sample of 0.5 to 1.5 ml, an internal standard solution was added
131 (^{13}C -labelled compounds from Cambridge Isotope Laboratories: Woburn, MA, USA). The
132 sample was extracted twice with 6 ml of *n*-hexane, after denaturation with ethanol and a
133 saturated solution of ammonium sulphate in water. Matrix removal on florisil columns,
134 separation on an Agilent Technology 7890 GC and detection on an Agilent Technology
135 5975C MSD were performed as described by Herzke et al. (2009). The limit for detection was
136 threefold the signal-to-noise ratio, and for the compounds investigated the limit ranged from
137 0.4 to 122 pg.g^{-1} wet weights (ww). For quality assurance, blanks (clean and empty glass
138 tubes treated like a sample) were run for every 10 samples similar to standard reference
139 material (1589 a human serum from NIST). The accuracy of the method was within the 70
140 and 108% range.

141

142 *2.4. Life history traits*

143 From 2007 to 2012, individuals were individually identified, through PVC plastic
144 bands reading. Using a mirror at the end of an 8 m fishing rod, we checked the whole plot
145 (about 120 nests) every two days to monitor breeding status (at least one egg is laid or no egg
146 laid). Then, we checked the nest content every 2 or 3 days to monitor the number of chicks
147 that reached at least 12 days of age per nest.

148

149 *2.5. Statistical analyses*

150 We used R software (R Development Core Team 2012) and generalized linear models
151 (GLMs) with normal distribution and a link function to test whether log-transformed Hg, Σ
152 PCBs, DDE, HCB or CHL levels were linked to sex, year and the interaction sex \times year.
153 GLMs with binomial error distribution and a logit link function were then used to test whether
154 breeding probability (will breed or will skip) the year of sampling was linked to pre-laying
155 Hg, Σ PCBs, DDE, HCB or CHL levels.

156

157 *2.6. Estimating the effect of Hg and POPs on demographic parameters*

158 The effects of Hg and POPs concentrations on the demographic parameters were
159 evaluated through the capture-recapture data of sampled kittiwakes. A MSMR (Multi-State
160 Mark Recapture, Lebreton and Pradel, 2002) model was constructed by distinguishing five
161 states: non-breeder (NB, defined as an individual that was not observed with an egg), failed
162 breeder (FB, defined as an individual that was observed with one or two eggs, or one or two
163 chicks but that failed to raise a chick), successful breeder with one chick (SB1, defined as an
164 individual that raised one chick), successful breeder with two chicks (SB2, defined as an
165 individual that raised two chicks), and dead. The state dead (\dagger) was an absorbing state
166 representing death or permanent emigration from the study area. Kittiwakes that were ringed
167 and observed the years before sampling for Hg or POPs were considered as non-observed, in

168 order to test the effect of contaminants (at year t) on future (year $t+1$) survival and breeding
169 performances. Models were parameterized in terms of the probability of survival (S), the
170 probability of breeding (β), the probability of breeding successfully (γ), the probability of
171 successfully raising two chicks (δ), and the detection probability (p). Transition probabilities
172 between states were thus modeled with a four-step procedure where S , β , γ and δ were
173 considered as four successive steps in transition matrices. Figure 1 presents a multinomial tree
174 diagram describing the probability structure for multistate observations, and parameters of the
175 model are defined in Table 2. We chose a MSMR approach since this allows taking into
176 account the probability of detecting individuals given their return to the study sites. It also
177 allows taking into account the previous breeding state of individuals which might be
178 important to obtain unbiased estimates of demographic parameters (Lebreton and Pradel
179 2002).

180 Several constraints were made to ensure that the parameters of the model were
181 estimable. The state “dead” being explicitly included in the model but being never
182 encountered, transition probabilities from the state dead were fixed to 0 and capture
183 probability was fixed to 0 (Pradel 2005, Choquet et al. 2009a). Because our capture-recapture
184 analyses relied on a limited number of individual capture histories, parameters S , β , γ , δ and p
185 were constrained to be constant over time but state and sex dependent. With this constraint the
186 initial model was full-rank. Note that we ran a model where all demographic parameters were
187 time, sex and state dependent but this model was highly rank deficient.

188 This MSMR model was parameterized by the survival–transition probabilities matrix:

189

	NB	FB	SB1	SB2	†
NB	$S(1 - \beta)$	$S\beta(1 - \gamma)$	$S\beta\gamma(1 - \delta)$	$S\beta\gamma\delta$	*
FB	$S(1 - \beta)$	$S\beta(1 - \gamma)$	$S\beta\gamma(1 - \delta)$	$S\beta\gamma\delta$	*
SB1	$S(1 - \beta)$	$S\beta(1 - \gamma)$	$S\beta\gamma(1 - \delta)$	$S\beta\gamma\delta$	*
SB2	$S(1 - \beta)$	$S\beta(1 - \gamma)$	$S\beta\gamma(1 - \delta)$	$S\beta\gamma\delta$	*
†	–	–	–	–	*

190

191 Because we were interested to test for sex-specific effects of Hg and POPs on
192 demographic parameters we started from an initial model including an effect of sex (g) on
193 each parameter. Model selection was first performed on detection probability by testing state-
194 dependency (difference between all states, between breeders and non-breeders, or no
195 difference). We then tested for sex difference and state-dependency (difference between all
196 states, difference between breeders and non-breeders or no difference) for S , β , γ and δ . We
197 tested for an effect of Hg, Σ PCBs, DDE, HCB, or CHL on demographic parameters the
198 following year to test the hypothesis that contamination levels in one breeding season may
199 influence the survival and breeding success of an individual in the following season. We built
200 MSMR models where each demographic parameter θ was modeled as a function of
201 contaminant C using a logit link function: $\text{logit}(\theta) = a + b \times C_i$, where a is an intercept, b is a
202 slope and C_i is Hg or POPs concentration for individual i . The 95% confidence interval (CI)
203 of the slope parameters b was used, as well as Akaike's Information Criterion corrected for
204 small sample size (AICc, Burnham and Anderson, 2002) for inference. We considered an
205 effect of contaminant as statistically supported when 0 was outside the 95% CI of the mean of
206 the slope of the relationship (Grosbois et al., 2008). When $b < 0$, or $b > 0$, the covariate C has
207 a negative or positive effect on the demographic parameter, respectively. We tested the
208 goodness-of-fit (GOF) of the time dependent MSMR model using U-CARE (Choquet et al.
209 2009b). All models were run under program E-SU RGE 1.8.5 allowing splitting transition
210 probabilities between states (Choquet et al. 2009a).

211

212 **3. Results**

213

214 *3.1 Associations between Hg or POPs and breeding probability in year of blood sampling*

215 Table 1 summarizes the values of Hg, \sum PCBs, DDE, HCB and CHL in males and
216 females. Appendix 1 gives the concentrations of each POP congener and appendix 2 presents
217 the relationships between levels of Hg, \sum PCBs, DDE, HCB and CHL.

218 Hg levels were significantly higher in males than in females ($F_{1,103} = 3.993$, $p =$
219 0.048), but did not differ between the two sampling years (year: $F_{1,102} = 3.339$, $p = 0.071$; sex
220 \times year: $F_{1,101} = 1.102$, $p = 0.296$). Breeding probability during the sampling year was
221 influenced by Hg levels ($df = 103$, $\chi^2 = 12.983$, $p < 0.001$): kittiwakes that would skip (mean
222 \pm SD: $2.284 \pm 0.417 \mu\text{g}\cdot\text{g}^{-1}$) had higher pre-laying Hg levels than kittiwakes that would breed
223 ($1.962 \pm 0.470 \mu\text{g}\cdot\text{g}^{-1}$).

224 Levels of \sum PCBs, DDE, HCB, or CHL did not differ between males and females
225 (sex: $p > 0.07$ for all tests: sex \times year: $p > 0.09$ for all tests). Levels of \sum PCBs ($F_{3,134} = 4.935$,
226 $p = 0.003$), HCB ($F_{3,134} = 37.035$, $p < 0.001$), \sum CHL ($F_{3,134} = 12.818$, $p < 0.001$), but not
227 DDE ($F_{3,134} = 2.519$, $p = 0.061$) differed among years. Breeding probability was not
228 influenced by levels of \sum PCBs, DDE, HCB, or CHL during the sampling year ($p > 0.61$ for
229 all tests).

230

231 *3.2. Associations between Hg and demographic parameters in year after blood sampling*

232 The GOF of the MSMR model was overall not significant (males: $\chi^2 = 48.913$, $df = 69$,
233 $p = 0.968$ and females: $\chi^2 = 47.435$, $df = 71$, $p = 0.986$). The best model according to AICc
234 (model 16, Appendix 3) indicated that breeders in the previous year had higher breeding
235 probabilities and detection probabilities than non-breeders in the previous year. However
236 birds captured as breeders or non-breeders did not differ in survival rate, probabilities of
237 successfully raising one or two chicks (Appendix 3 and Table 3). Demographic parameters
238 did not differ between males and females (Appendix 3 and Table 3).

239 Model selection and slope estimates suggested no effect of Hg on demographic
240 parameters. Model Hg3 had a ΔAICc lower than 2 compared to the null model, but the effect
241 of Hg on breeding probability the following year was not supported, since the 95% CI of the
242 slope parameter included 0 (Table 4).

243

244 *3.3. Associations between POPs and demographic parameters in year after blood sampling*

245 Model selection was based on ΔAICc higher than 2 compared to the intercept model
246 and the 95% CI of the slope of the relationship that did not include zero. Hence, in spite of
247 good AICc, several models suggesting an effect of Σ PCBs, DDE, HCB or CHL on
248 demographic parameters were not retained. Only six models met these requirements (Table
249 5). Models HCB5 and HCB6 suggested a negative effect of HCB on breeding probability the
250 following year for individuals and especially males observed as breeders (Fig.2A, 2B).
251 Model CHL6 suggested a negative effect of CHL on breeding probability the following year
252 for males observed as breeders (Fig. 2C). Model HCB1 suggested a positive effect of HCB on
253 the probability of successfully raising two chicks the following year (Fig. 3). Model HCB8
254 suggested a negative effect of HCB on survival rate of females (Fig. 4A). Model CHL7
255 suggested a negative effect of CHL on survival rate (Fig. 4B). We could also notice a
256 tendency towards a negative effect between survival rates and levels of Σ PCBs (model
257 PCB7, $\Delta\text{AICc} = 1.24$, mean slope and 95% CI = -0.44 [-0.82 ; -0.03]), DDE (Model: DDE7,
258 $\Delta\text{AICc} = 0.88$, slope = -0.42 [-0.82 ; -0.01]), HCB for males and females (Model HCB7,
259 $\Delta\text{AICc} = 1.73$, slope = -0.47 [-0.88 ; -0.06]), or CHL for females only (Model CHL8, ΔAICc
260 = 1.50, slope = -0.73 [-1.29 ; -0.17]).

261

262 **4. Discussion**

263 Using a long-term data set and MSMR models, this study explores the demographic
264 effects of Hg or families of legacy POPs (7 PCB congeners, p-p' DDE, HCB, and the
265 chlordane mixture and metabolites (trans-chlordane, trans-, cis-nonachlor, oxychlordane)) in a
266 free-living Arctic seabird species. It should be noticed that differences in toxicity among POP
267 congeners were not taken into account in these analyses, because toxic equivalent factors
268 (TEFs) were only available for PCB-105 and PCB-118. Moreover interactions among families
269 of pollutants may occur within an organism to induce synergistic effects, but they are difficult
270 to demonstrate within a field study.

271

272 *4.1. Survival and contaminants*

273 Estimated demographic parameters were similar to those previously estimated in other
274 populations of black legged kittiwakes (Frederiksen et al., 2005). Adult survival rate in this
275 study (85% [82 – 88%]) was within the range of estimated survival rates in north Atlantic
276 populations (80-92%, Danchin and Monnat, 1992; Erikstad et al., 1995; Oro and Furness,
277 2002; Frederiksen et al., 2005).

278 The adult survival rate of kittiwakes was not jeopardized by Hg, which corroborates
279 most of the previous studies in free-living birds (Wayland et al., 2008; Hallinger et al., 2011;
280 Goutte et al., 2014a,b). Apparent survival rate was negatively linked to HCB levels in
281 females, to mixture of chlordane and oxychlordane, and tended to be negatively correlated
282 with \sum PCBs or DDE levels. Only one study (Erikstad et al. 2013) highlighted a negative
283 effect of oxychlordane on adult survival rate in the glaucous gull breeding in the Bjørnøya
284 Island (blood levels of oxychlordane: 1.3 to 128.8 ng.g⁻¹ wet weight, median: 13.2 ng.g⁻¹ ww)
285 and this effect was the most pronounced among the most contaminated females. Even if
286 kittiwakes were more than 10-time less contaminated than glaucous gull (blood levels of
287 oxychlordane: 0.007 to 6.0 ng.g⁻¹ wet weight), this study reveals that high levels of the

288 chlordanes mixture and metabolites or HCB could negatively affect adult survival rate, and
289 especially in female kittiwakes.

290 The correlation between POP levels and survival rate could be a by-product of age-
291 dependent mechanisms, with older kittiwakes having the highest POP burden and the lowest
292 survival probability. Age of kittiwakes was unknown in this study and we could not control
293 for age. However, blood levels of PCB-153, p,p'-DDE, HCB, and oxychlordanes were
294 unrelated to age in glaucous gulls (Bustnes et al., 2003b). Similarly, blood levels of PCBs or
295 organochlorine pesticides (HCB, lindane, chlordanes mixture, mirex, DDT and metabolites)
296 were unrelated to age in wandering albatrosses (Carravieri et al., 2014). Therefore, it seems
297 unlikely that age was a confounding factor in the correlation between POP levels and survival
298 rate. In addition, as we did not monitor long-distance dispersal, our findings on apparent
299 survival rate could also include the effects of POPs on long-term emigration of the most
300 polluted birds.

301 This study suggests that HCB or the chlordanes mixture and metabolites may weaken
302 the general health of kittiwakes and may increase their vulnerability to harsh environmental
303 pressures in the Arctic (Letcher et al., 2010). In that context, it is conceivable that the effect
304 of POPs on survival rate is only detected during harsh environmental events. Because our
305 sample size did not allow taking into account an effect of years, we could not have tested
306 whether harsh environmental conditions during a specific year would exacerbate the effects of
307 pollutants on demographic parameters the following year.

308

309 *4.2. Long-term fecundity and contaminants*

310 A previous study on this population of kittiwakes has highlighted that total blood Hg
311 load during the pre-laying period predicted the likelihood of breeding, with non-breeders
312 having higher Hg levels than breeders, but not the timing of breeding, clutch size, and

313 breeding success (Tartu et al., 2013). Moreover experimentally elevated Hg levels (total Hg in
314 blood, mean \pm SD: from 0.73 ± 0.09 to 3.95 ± 0.68 mg.kg⁻¹ fresh weight) led to an altered
315 pairing behaviour in white ibises *Eudocimus albus* (Frederick and Jayasena, 2011). In the
316 present study, Hg levels were higher in kittiwakes that would skip breeding than in birds that
317 would breed, as previously shown (Tartu et al., 2013). Hg levels did not affect breeding
318 probability and breeding success the following year, which differed from previous studies in
319 the south polar skua *Catharacta maccormicki* (Hg levels in blood: mean \pm SE: 2.15 ± 0.17
320 $\mu\text{g.g}^{-1}$ dry mass), in the brown skua *C. lonnbergi* (8.22 ± 0.24 $\mu\text{g.g}^{-1}$ dry mass) and in the
321 wandering albatross (7.7 ± 3.6 $\mu\text{g.g}^{-1}$ dry mass) (Goutte et al., 2014 a,b). However, Hg levels
322 in these species were measured during the incubation and the chick-rearing period, while Hg
323 levels in the present study were measured in pre-laying kittiwakes. Furthermore, breeding
324 success was monitored on chicks that reached at least 12 days of age and did not allow testing
325 an effect of contaminants on late developmental stage.

326 POPs burden did not influence the breeding probability the year of sampling, which
327 was consistent with a previous study on the same population of kittiwakes (Tartu et al. 2014).
328 Breeding probability the following years was reduced by high HCB levels in breeders and
329 especially in males, or by high levels of the chlordanes mixture and metabolites in male
330 breeders. A negative correlation between POP levels and breeding probabilities the following
331 year has been highlighted in the wandering albatross (Goutte et al., 2014b). Male breeders
332 seemed to be the most sensitive to POPs. Energetic and time-dependent costs of reproduction
333 have been shown to induce downstream consequences on reproductive investment during the
334 following breeding season (carry over effect, Catry et al., 2013). One may suggest that POPs
335 burden may intensify these carry over effects, but studies are needed to either rebut or confirm
336 this hypothesis.

337 Levels of Σ PCB, DDE, HCB, and the chlordane mixture and metabolites did not
338 influence the probability of successfully raising one chick the following year, which was
339 consistent with a previous study on the same population of kittiwakes and during the year of
340 sampling (Tartu et al., 2014). We detected a positive relationship between the probability of
341 successfully raising two chicks the following year and HCB levels, but not PCBs, DDE or the
342 chlordane mixture. This positive relationship between HCB and breeding performance
343 appears surprising, as contaminants are believed to induce deleterious effects on reproductive
344 traits. Previous studies have pointed out that female kittiwakes and gulls with higher levels of
345 organochlorine pesticides laid their eggs earlier in the season (Bustnes et al., 2008; Tartu et
346 al., 2014). As laying early is related to high breeding success (Lack, 1968), this could explain
347 the positive relationship between HCB and the probability of successfully raising two chicks.
348 In another hand, this relationship may not be causal and may be enhanced by confounding
349 factors: for instance, kittiwakes succeeding in raising two chicks may be of higher quality,
350 rely on higher trophic level organisms and hence be more exposed to pollutant.

351

352 It appears that some families of POPs may be more prone to trigger damaging effects
353 the following year. Specifically, high levels of HCB or the chlordane mixture and metabolites
354 were correlated to lower survival rate and lower probability to breed the following year. These
355 findings corroborate a previous study: despite their lower concentrations, HCB and
356 oxychlordane tended to be more often related to adverse effects than PCB and DDE in
357 glaucous gull (Bustnes, 2006). Although levels of these “legacy” POPs are expected to
358 decline, as shown in Canadian Arctic seabirds from the 1970s to the late 1990s (Braune et al.,
359 2005), they appear to represent a potential threat for adult survival rate and thus for
360 population dynamics.

361

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372

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509

510 Table 1: Levels (mean \pm SD) of Σ PCBs (CB, -99, -118, -138, -153, -180, -183 and -187),
 511 p,p'-DDE, HCB, CHL (transchlordan, trans-, cis-nonachlor, oxychlordan,) and Hg
 512 (mercury) in blood of male and female kittiwakes sampled during the pre-laying period.

	Year	Males	Females
Σ PCBs (pg.g ⁻¹ ww)	2007	14700 \pm 9630	12640 \pm 6421
	2008	14896 \pm 11029	13399 \pm 9197
	2009	9282 \pm 7915	10375 \pm 4705
	2010	12786 \pm 10966	21168 \pm 14390
DDE (pg.g ⁻¹ ww)	2007	3622 \pm 1730	3152 \pm 1422
	2008	4025 \pm 2642	4189 \pm 3490
	2009	2618 \pm 1660	2184 \pm 890
	2010	3249 \pm 2739	4725 \pm 3584
HCB (pg.g ⁻¹ ww)	2007	1616 \pm 966	1600 \pm 407
	2008	1616 \pm 444	1691 \pm 697
	2009	2416 \pm 1493	2699 \pm 451
	2010	2670 \pm 877	3487 \pm 1288
CHL (pg.g ⁻¹ ww)	2007	1352 \pm 782	1329 \pm 508
	2008	1237 \pm 510	1275 \pm 765
	2009	1344 \pm 1155	1353 \pm 403
	2010	1766 \pm 650	2482 \pm 1602
Hg (μ g.g ⁻¹ dw)	2008	2.06 \pm 0.44	1.97 \pm 0.44
	2009	2.33 \pm 0.55	2.01 \pm 0.41

513

514

515 Table 2 Definition of parameters used in the multistate mark–recapture model

Parameter	Definition
S_s^t	Probability that an individual in state s at time t survives to time $t + 1$ and does not permanently emigrate from the study area
β_s^t	Probability that an individual in state s at time t breeds at time $t + 1$ given that it survives to $t + 1$
γ_s^t	Probability that an individual in state s at time t breeds successfully at time $t + 1$ given that it survives to and breeds at time $t + 1$
δ_s^t	Probability that an individual in state s at time t raises successfully two chicks at time $t + 1$ given that it survives to and breeds successfully at time $t + 1$
p_s^t	Probability that an individual in state s at time t is encountered at time $t + 1$

516

517 Table 3: Estimation of parameters (mean and CI) calculated from the best model (model 16,
 518 Appendix 3) for breeders and non-breeders.

	Non-breeders	Breeders
S : apparent survival rate (%)	85 [82 ; 88]	85 [82 ; 88]
β : Breeding probability (%)	47 [41 ; 53]	82 [78 ; 86]
γ : Breeding success (%)	75 [71 ; 79]	75 [71 ; 79]
δ : Probability of raising 2 chicks (%)	40 [35; 45]	40 [35; 45]
p : Detection probability (%)	78 [67 ; 85]	98 [90 ; 99]

519

520 Table 4: Modeling the effects of Hg levels and sex on demographic parameters of *Rissa*
521 *tridactyla* (N = 105). Models are arranged from lowest to highest ΔAICc . The estimated slope
522 and 95% confidence intervals (CI) are given for the model (Hg3) that has a
523 lower AICc than the intercept model.
524

Hypothesis	# Model	Rank	Deviance	ΔAICc	Slope	95% CI
Effect of Hg on γ	Hg3	12	1194.84	0	0.29	-0.84 ; 1.43 #
Intercept model	Hg0	10	1201.22	2.10		
Effect of Hg on δ	Hg1	12	1197.40	2.56		
Effect of Hg and sex on γ	Hg4	14	1193.67	3.18		
Effect of Hg and sex on δ	Hg2	14	1194.82	4.33		
Effect of Hg on S	Hg7	12	1201.11	6.28		
Effect of Hg on β	Hg5	14	1197.90	7.41		
Effect of Hg and sex on β	Hg6	18	1190.66	9.03		
Effect of Hg and sex on S	Hg8	14	1200.50	10.01		

525 # This effect is not supported because the 95% confidence intervals of the mean of the slope
526 of the relationship included zero.

527 Table 5: Modeling the effects of Σ PCBs, p,p'-DDE, HCB and CHL levels and sex on
528 demographic parameters of *Rissa tridactyla* (N = 138). Models are arranged from lowest to
529 highest Δ AICc. The estimated slopes and 95% confidence intervals (CI) are given for models
530 that have a lower AICc than the intercept model (NB: non-breeders, B: breeders).

531

Hypothesis	# Model	Rank	Deviance	Δ AICc	Slope	95% CI	
Effect of Σ PCBs on β	PCB5	14	1351.03	0	NB : -0.62	-1.48 ; 0.23	#
					B : -0.14	-0.82 ; 0.53	#
Effect of Σ PCBs and sex on β	PCB6	18	1344.22	1.90	Male NB : -0.36	-1.50 ; 0.78	#
					Male B : -1.10	-2.43 ; 0.22	#
					Female NB : -0.87	-2.21 ; 0.46	#
					Female B : 0,83	-0.38 ; 2.06	#
Effect of Σ PCBs on S	PCB7	12	1366.07	10.75	-0.44	-0.82 ; -0.03	##
Effect of Σ PCBs on δ	PCB1	12	1367.05	11.74	0.47	-0,36 ; 1,31	###
Intercept model	PCB0	10	1371.55	11.99			
Effect of Σ PCBs and sex on δ	PCB2	14	1364.06	13.03			
Effect of Σ PCBs and sex on S	PCB8	14	1364.33	13.30			
Effect of Σ PCBs on γ	PCB3	12	1368.92	13.61			
Effect of Σ PCBs and sex on γ	PCB4	14	1368.69	17.66			
Effect of DDE and sex on β	DDE6	18	1339.67	0	Male NB : -0.26	-1.78 ; 1.26	#
					Male B : -1.17	-2.44 ; 0.10	#
					Female NB : -1.82	-3.79 ; 0.14	#
					Female B : 0.69	-0.64 ; 2.01	#
Effect of DDE on β	DDE5	14	1349.00	0.61	NB : -1.00	-2.08 ; 0.08	#
					B : -0.14	-0.70 ; 0.42	#
Effect of DDE on S	DDE7	12	1366.43	13.76	-0.42	-0.82 ; -0.01	##
Intercept model	DDE0	10	1371.55	14.64			
Effect of DDE on δ	DDE1	12	1367.91	15.24			
Effect of DDE on γ	DDE3	12	1368.85	16.18			
Effect of DDE and sex on S	DDE8	14	1365.94	17.56			
Effect of DDE and sex on δ	DDE2	14	1366.73	18.35			
Effect of DDE and sex on γ	DDE4	14	1368.19	19.80			
Effect of HCB and sex on β	HCB6	18	1339.36	0	Male NB : -1.50	-4.24 ; 1.25	#
					Male B : -1.86	-3.38 ; -0.34	#
					Female NB : -0.02	-0.87 ; 0.92	#
					Female B : 0.08	-0.74 ; 0.90	#

Effect of HCB on β	HCB5	14	1349.44	1.37	NB : -0.28 B : -0.53	-1.06 ; 0.50 -1.04 ; -0.01	#
Effect of HCB and sex on δ	HCB2	14	1357.05	8.98	NB : -0.18 B : -2.27	-0.57 ; 0.21 -0.15 ; 4.69	# #
Effect of HCB on δ	HCB1	12	1362.22	9.86	0.94	0.10 ; 1.79	
Effect of HCB and sex on S	HCB8	14	1360.54	12.47	Male : 0.41 Female : -0.82	-0.75 ; 1.57 -1.39 ; -0.25	#
Effect of HCB on S	HCB7	12	1365.58	13.22	-0.47	-0.88 ; -0.06	##
Intercept model	HCB0	10	1371.55	14.95			
Effect of HCB on γ	HCB3	12	1369.19	16.83			
Effect of HCB and sex on γ	HCB4	14	1367.08	19.01			
Effect of CHL and sex on β	CHL6	18	1338.80	0	Male NB : -0.59 Male B : -2.64 Female NB : -0.73 Female B : -0.07	-2.95 ; 1.77 -5.09 ; -0.18 -1.98 ; 0.51 -0.85 ; 0.70	# # #
Effect of CHL on β	CHL5	14	1347.61	0.10	NB : -0.73 B : -0.59	-1.81 ; 0.34 -1.20 ; 0.01	# #
Effect of CHL on S	CHL7	12	1363.00	11.20	-0.57	-1.00 ; -0.13	
Effect of CHL and sex on δ	CHL2	14	1359.59	12.08	NB : 1.46 B : 1.85	-1.23 ; 4.15 -0.23 ; 3.93	# #
Effect of CHL on δ	CHL1	12	1363.83	12.03	1.05	-0.15 ; 2.24	#
Effect of CHL and sex on S	CHL8	14	1361.52	14.01	Male : -0.04 Female : -0.73	-1.12 ; 1.04 -1.29 ; -0.17	### ##
Intercept model	CHL0	10	1371.55	15.51			
Effect of CHL on γ	CHL3	12	1368.41	16.61			
Effect of CHL and sex on γ	CHL4	14	1368.38	20.87			

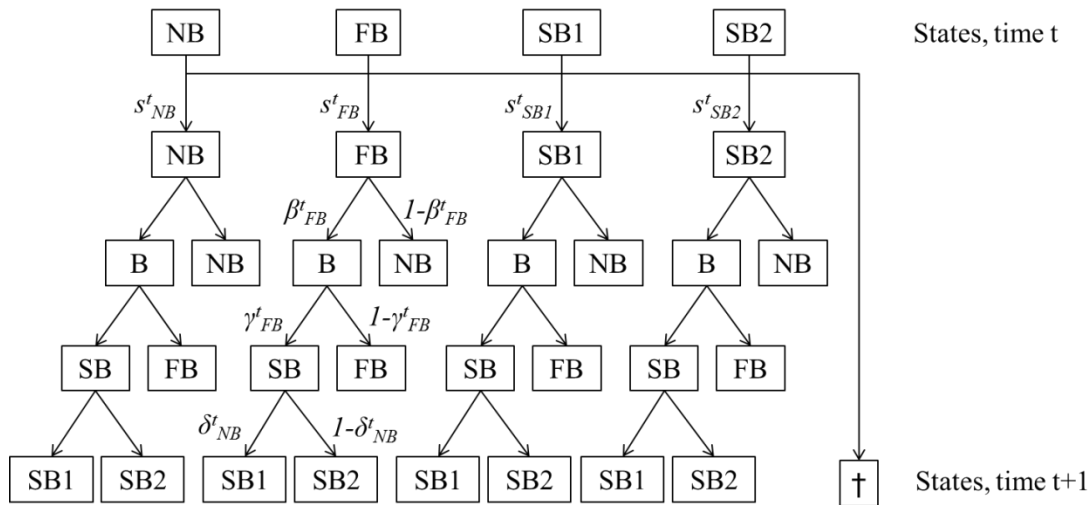
This effect is not supported, because the 95% CI of the mean of the slope of the relationship included zero.

This effect is not supported, because the model has a $\Delta AICc < 2$ compared to the intercept model

532 ### This effect is not supported, because the 95% CI of the mean of the slope of the relationship
533 included zero and the model has a $\Delta AICc < 2$ compared to the intercept model.

534 Figure 1: A multinomial tree diagram describing the probability structure for multistate
 535 observations. Solid boxes indicate the states alive in state NB (non-breeder), FB (failed
 536 breeder), SB1 (successful breeder with one chick), SB2 (successful breeder with two chicks).
 537 dead. State transition probabilities were decomposed in a four-step process. The state
 538 transitions (S, β, γ, δ) are defined in Table 2 and states in the Methods section.

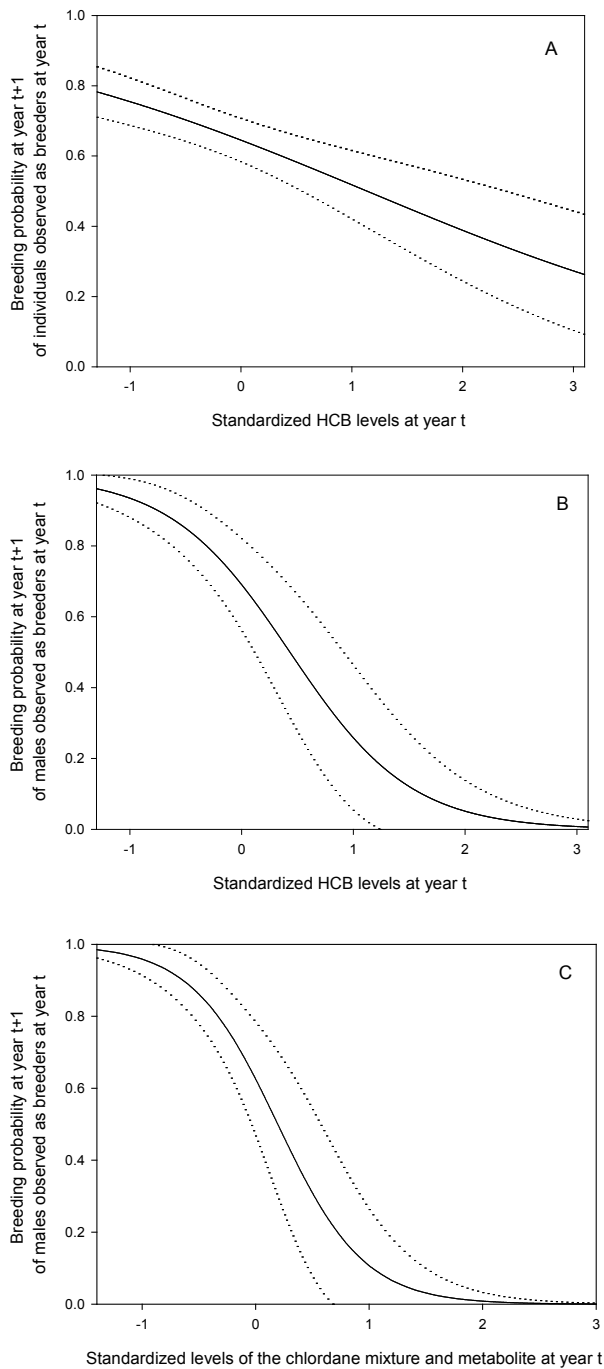
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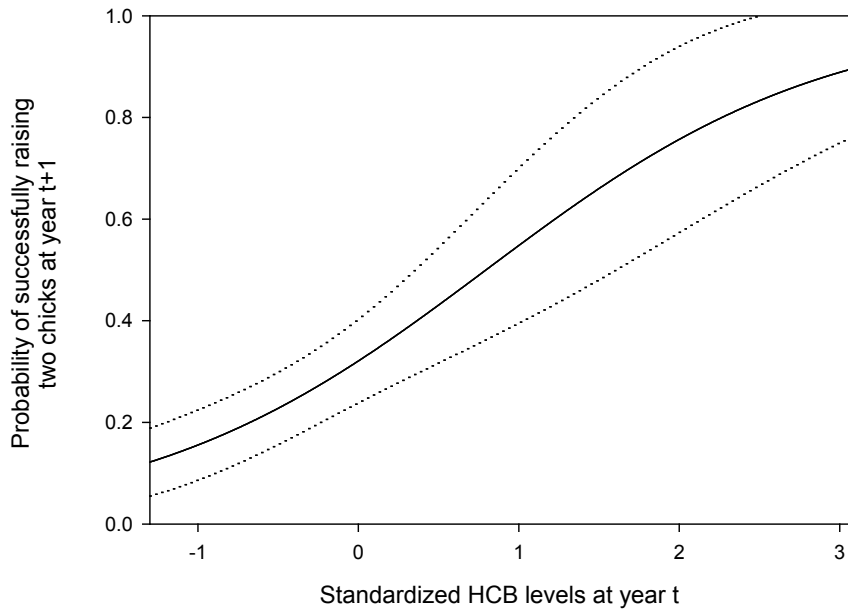
541

542 Figure 2: Relationship between breeding probability at year t+1 in black-legged kittiwakes
543 and (A) standardized HCB levels in individuals observed as breeders at year t, (B)
544 standardized HCB levels in males observed as breeders at year t and (C) standardized levels
545 of the chlordane mixture and metabolites in males observed as breeders at year t . Dotted lines
546 represent 95% CI.



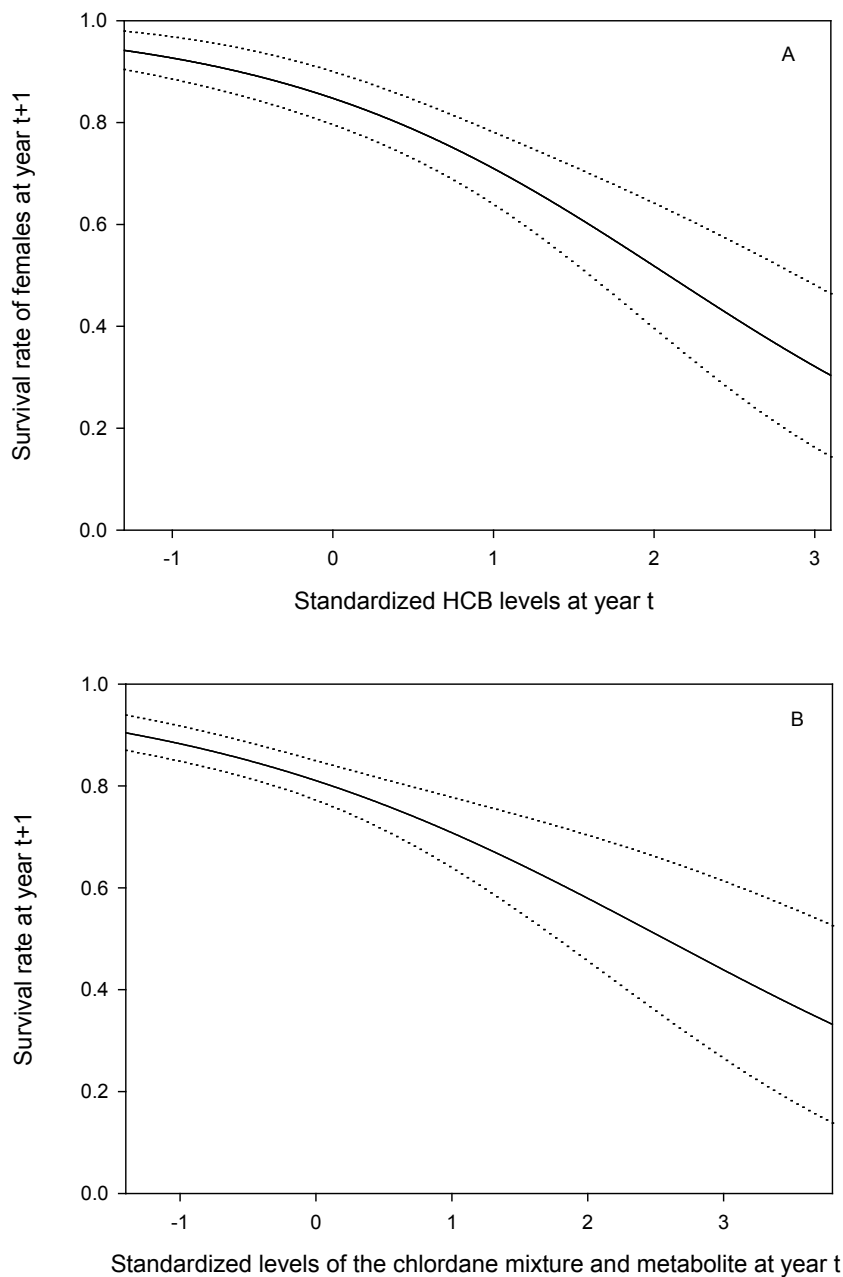
547

548 Figure 3: Relationship between probability of successfully raising two chicks at year t+1 in
549 black-legged kittiwakes and standardized HCB levels at year t.



550

551 Figure 4: Relationship between survival rate at year t+1 in black-legged kittiwakes and (A)
552 standardized HCB levels in females at year t, (B) standardized levels of the chlordane mixture
553 and metabolites at year t.



554

555 Appendix 1: Concentrations (mean, median and standard deviation SD, in pg.g-1 ww)
556 measured for each POP congener in 138 black-legged kittiwakes during the pre-laying period.
557

Congener	Mean	Median	SD
PCB-99	1069	800	869
PCB-118	1638	1313	1217
PCB-138	4104	2856	3463
PCB-153	5498	4159	3979
PCB-180	1888	1513	1832
PCB-183	537	354	591
PCB-187	932	680	867
p,p' DDE	3892	2978	2900
HCB	2418	2026	1262
translordane	322	217	346
oxychlorane	1002	818	786
cisnonachlor	173	158	100
transnonachlor	216	196	142

558

559 Appendix 2: Relationships between Hg, Σ PCBs, DDE, HCB, and CHL levels

560

561

	Σ PCB	DDE	HCB	CHL
DDE	$F_{1,136} = 180, p < 0.001$			
HCB	$F_{1,136} = 63, p < 0.001$	$F_{1,136} = 41, p < 0.001$		
CHL	$F_{1,136} = 129, p < 0.001$	$F_{1,136} = 104, p < 0.001$	$F_{1,136} = 201, p < 0.001$	
Hg	$F_{1,35} < 0.01 \quad p = 0.983$	$F_{1,35} = 0.04 \quad p = 0.839$	$F_{1,35} = 2.77 \quad p = 0.105$	$F_{1,35} = 1.33 \quad p = 0.136$

562

563

564 Appendix 3:

565 Initial model (Model1) considers sex-difference and state-difference on S , β , γ , δ , and
 566 p . A. Modelling the effect of states on p . B. Modelling the effect of sex on s , β , γ and δ , with p
 567 being different between breeders and non-breeders. C. Modelling the effect of states on s , β , γ
 568 and δ (δ is necessarily constant).

569

A. Hypothesis	# Model	Rank	Deviance	$\Delta AICc$
p differs between NB and B	Model2	31	3630,77	0
p is state-dependent	Model1	33	3630,23	3,73
p is constant	Model3	30	3642,96	10,06

B. Hypothesis	# Model	Rank	Deviance	$\Delta AICc$
No sex difference on S, β, γ and δ	Model8	18	3636,86	0
Sex difference on S , β and δ	Model5	27	3632,09	14,08
Sex difference on S , γ and δ	Model6	27	3632,90	14,88
Sex difference on β , γ and δ	Model7	27	3633,21	15,19
Sex difference on S , β and γ	Model4	30	3630,77	19,11
Sex difference on S , β , γ and δ	Model2	31	3630,77	21,24

C. Hypothesis	# Model	Rank	Deviance	$\Delta AICc$
S and γ are constant; β is state-dependent	Model15	12	3640,14	0
S and γ are constant; β differs between NB and B	Model16	10	3644,82	0,59
S , β and γ are constant	Model17	11	3644,79	2,61
γ is constant; S and β are state-dependent	Model10	15	3638,35	4,38
S is constant; β and γ are state-dependent	Model14	15	3638,68	4,72
S differs between NB and B; β and γ are state-dependent	Model13	16	3637,55	5,64
S , β and γ are state-dependent	Model8	18	3636,86	9,10
β differs between NB and B; S and γ are state-dependent	Model11	16	3641,59	9,69
γ differs between NB and B; S and β are state-dependent	Model9	16	3678,02	46,12
β is constant; S and γ are state-dependent	Model12	15	3725,68	91,71

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