

Ecography

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Integrated population model reveals that kestrels
breeding in nest boxes operate as a source population.
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Supplementary material

1 **Appendix 1.** Multistate mark-recapture model used in the integrated population model to analyze
2 capture-mark-recapture and recovery data.

3

4 True states:

5 1: juvenile alive, aluminum ring

6 2: adult alive, aluminum ring

7 3: adult alive physically captured and alphanumeric ring fixed,

8 4: adult alive resighted with alphanumeric ring

9 5: recently dead

10 6: long time dead

11

12 Transition matrix

$$\begin{pmatrix} 0 & S_1(1-a) & S_1a & 0 & 1-S_1 & 0 \\ 0 & S_2(1-a) & S_2a & 0 & 1-S_2 & 0 \\ 0 & 0 & 0 & S_2 & 1-S_2 & 0 \\ 0 & 0 & 0 & S_2 & 1-S_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}^t$$

13

14 Vector with state-specific recapture probabilities

$$\begin{bmatrix} 0 & p & 1 & c & r & 0 \end{bmatrix}^t$$

15

16

17 Parameters:

18 S_1 : Juvenile survival

19 S_2 : Adult survival

20 a : Probability that an alphanumeric ring is fixed on an individual

21 p : Recapture probability of an adult with aluminum ring only

22 c : Resighting probability of an adult with both aluminum and an alphanumeric ring

23 r : Dead recovery probability

24

25 **Appendix 2.** JAGS code to fit the integrated population model for the Swiss Eurasian kestrel
26 (*Falco tinnunculus*) population breeding in nest-boxes.

```
27 cat(file = "ipm.jags", "  
28     model {  
29  
30     ### Priors and constraints  
31  
32     # Demographic traits  
33     for (t in 1:(n.occasions-1)){  
34         sj[t] <- 1/(1+exp(-logit.sj[t]))  
35         logit.sj[t] ~ dnorm(l.mean.sj, tau.sj)  
36         sa[t] <- 1/(1+exp(-logit.sa[t]))  
37         logit.sa[t] ~ dnorm(l.mean.sa, tau.sa)  
38         a[t] <- 1/(1+exp(-logit.a[t]))  
39         logit.a[t] ~ dnorm(l.mean.a, tau.a)  
40         p[t] <- 1/(1+exp(-logit.p[t]))  
41         logit.p[t] ~ dnorm(l.mean.p, tau.p)  
42         c[t] <- 1/(1+exp(-logit.c[t]))  
43         logit.c[t] ~ dnorm(l.mean.c, tau.c)  
44         r[t] <- 1/(1+exp(-logit.r[t]))  
45         logit.r[t] ~ dnorm(l.mean.r, tau.r)  
46         p.success[t] <- 1/(1+exp(-logit.p.success[t]))  
47         logit.p.success[t] ~ dnorm(l.mean.p.success, tau.p.success)  
48         prod[t] ~ dnorm(mean.prod, tau.prod)  
49         I[t] ~ dnorm(mean.I, tau.I)  
50     }  
51  
52     l.mean.sj <- log(mean.sj / (1-mean.sj))  
53     mean.sj ~ dunif(0, 1)  
54     l.mean.sa <- log(mean.sa / (1-mean.sa))  
55     mean.sa ~ dunif(0, 1)  
56     l.mean.a <- log(mean.a / (1-mean.a))  
57     mean.a ~ dunif(0, 1)  
58     l.mean.p <- log(mean.p / (1-mean.p))  
59     mean.p ~ dunif(0, 1)  
60     l.mean.c <- log(mean.c / (1-mean.c))  
61     mean.c ~ dunif(0, 1)  
62     l.mean.r <- log(mean.r / (1-mean.r))  
63     mean.r ~ dunif(0, 1)  
64     l.mean.p.success <- log(mean.p.success / (1-mean.p.success))  
65     mean.p.success ~ dunif(0, 1)  
66     mean.prod ~ dunif(0, 10)  
67     mean.I ~ dunif(-5, 5)  
68  
69     tau.sj <- pow(sigma.sj, -2)  
70     sigma.sj ~ dunif(0.001, 10)  
71     tau.sa <- pow(sigma.sa, -2)  
72     sigma.sa ~ dunif(0.001, 10)  
73     tau.a <- pow(sigma.a, -2)  
74     sigma.a ~ dunif(0.001, 10)
```

```

75     tau.p <- pow(sigma.p, -2)
76     sigma.p ~ dunif(0.001, 10)
77     tau.c <- pow(sigma.c, -2)
78     sigma.c ~ dunif(0.001, 10)
79     tau.r <- pow(sigma.r, -2)
80     sigma.r ~ dunif(0.001, 10)
81     tau.prod <- pow(sigma.prod, -2)
82     sigma.prod ~ dunif(0.001, 20)
83     tau.prod <- pow(sigma.prod, -2)
84     sigma.prod ~ dunif(0.001, 20)
85     tau.p.success <- pow(sigma.p.success, -2)
86     sigma.p.success ~ dunif(0.001, 3)
87     tau.I <- pow(sigma.I, -2)
88     sigma.I ~ dunif(0.001, 5)
89
90     # Population count
91     sigma.fit ~ dunif(0, 50)
92     tau.fit <- pow(sigma.fit, -2)
93
94     # Derived and other quantities
95     mean.fec <- mean(fec)
96     mean.lambda <- mean(lambda)
97
98     # Define state-transition and observation probabilities for the
99     mark-recapture-recovery model
100    for (t in 1:(n.occasions-1)){
101        ps[1,t,1] <- 0
102        ps[1,t,2] <- sj[t]*(1-a[t])
103        ps[1,t,3] <- sj[t]*a[t]
104        ps[1,t,4] <- 0
105        ps[1,t,5] <- 1-sj[t]
106        ps[1,t,6] <- 0
107
108        ps[2,t,1] <- 0
109        ps[2,t,2] <- sa[t]*(1-a[t])
110        ps[2,t,3] <- sa[t]*a[t]
111        ps[2,t,4] <- 0
112        ps[2,t,5] <- 1-sa[t]
113        ps[2,t,6] <- 0
114
115        ps[3,t,1] <- 0
116        ps[3,t,2] <- 0
117        ps[3,t,3] <- 0
118        ps[3,t,4] <- sa[t]
119        ps[3,t,5] <- 1-sa[t]
120        ps[3,t,6] <- 0
121
122        ps[4,t,1] <- 0
123        ps[4,t,2] <- 0
124        ps[4,t,3] <- 0
125        ps[4,t,4] <- sa[t]

```

```

126     ps[4,t,5] <- 1-sa[t]
127     ps[4,t,6] <- 0
128
129     ps[5,t,1] <- 0
130     ps[5,t,2] <- 0
131     ps[5,t,3] <- 0
132     ps[5,t,4] <- 0
133     ps[5,t,5] <- 0
134     ps[5,t,6] <- 1
135
136     ps[6,t,1] <- 0
137     ps[6,t,2] <- 0
138     ps[6,t,3] <- 0
139     ps[6,t,4] <- 0
140     ps[6,t,5] <- 0
141     ps[6,t,6] <- 1
142
143
144     po[1,t,1] <- 0
145     po[1,t,2] <- p[t]
146     po[1,t,3] <- 1
147     po[1,t,4] <- c[t]
148     po[1,t,5] <- r[t]
149     po[1,t,6] <- 0
150
151     for (s in 2:ns){
152       for (u in 1:ns){
153         po[s,t,u] <- po[1,t,u]
154       } # u
155     } # s
156
157     for (s in 1:ns){
158       for (u in 1:ns){
159         qo[s,t,u] <- 1-po[s,t,u]
160       } # u
161     } # s
162   } # t
163
164
165   ### Define the multinomial likelihood for the mark-recapture-
166   recovery model (data in m-array format)
167
168   for (t in 1:((n.occasions-1)*ns)){
169     marr[t,1:(n.occasions*ns-(ns-1))] ~ dmulti(pr[t, ], rel[t])
170   }
171
172   ## Define the cell probabilities of the m-array
173   # Define matrix Q: product of probabilities of survival and
174   non-capture
175   for (t in 1:(n.occasions-2)){
176     Q[(t-1)*ns+(1:ns), (t-1)*ns+(1:ns)] <- ones

```

```

177     for (j in (t+1):(n.occasions-1)){
178         Q[(t-1)*ns+(1:ns), (j-1)*ns+(1:ns)] <- Q[(t-1)*ns+(1:ns),
179             (j- 2)*ns+(1:ns)] %*% (ps[,t,] * qo[,t,])
180     }
181 }
182
183 Q[(n.occasions-2)*ns+(1:ns), (n.occasions-2)*ns+(1:ns)] <- ones
184
185 # Define the cell probabilities of the multistate m-array
186 # The main diagonal
187 for (t in 1:(n.occasions-2)){
188     pr[(t-1)*ns+(1:ns),(t-1)*ns+(1:ns)] <- Q[(t-1)*ns+(1:ns),
189         (t-1)*ns+(1:ns)] %*% (ps[,t,] * po[,t,])
190
191     # Above main diagonal
192     for (j in (t+1):(n.occasions-1)){
193         pr[(t-1)*ns+(1:ns), (j-1)*ns+(1:ns)] <- Q[(t-1)*ns+(1:ns),
194             (j-1)*ns+(1:ns)] %*% (ps[,j,] * po[,j,])
195     }
196 }
197
198 pr[(n.occasions-2)*ns+(1:ns), (n.occasions-2)*ns+(1:ns)] <-
199 ps[,n.occasions-1,] * po[,n.occasions-1,]
200
201 # Below main diagonal
202 for (t in 2:(n.occasions-1)){
203     for (j in 1:(t-1)){
204         pr[(t-1)*ns+(1:ns),(j-1)*ns+(1:ns)] <- zero
205     } #j
206 } #t
207
208 # Last column: probability of non-recapture
209 for (t in 1:((n.occasions-1)*ns)){
210     pr[t,(n.occasions*ns-(ns-1))] <- 1-sum(pr[t,1:((n.occasions-
211 1)*ns)])
212 } #t
213
214 ## Likelihood for logistic and normal regression models for
215 reproductive success and productivity data
216 for (t in 1:(n.occasions-1)){
217     n.success[t] ~ dbin(p.success[t], n.brood[t])
218     for (i in 1: n.product[t]){
219         n.chick[i,t] ~ dnorm(prod[t], tau.prod)
220     }
221     fec[t] <- p.success[t] * prod[t]
222 }
223
224 ## Likelihood for the state-space model
225 # Initial state
226 N[1,1] ~ dunif(5, 25)
227 N[2,1] ~ dunif(5, 25)

```

```

228
229 # Population projection (state process)
230 for (t in 1:(n.occasions-1)){
231   N[1,t+1] <- fec[t]/2 * sj[t] * (0.35*N[1,t] + N[2,t]) + (N[1,t]
232 +
233   N[2,t]) * I[t]
234   N[2,t+1] <- sa[t] * (N[1,t] + N[2,t])
235
236   # Growth rate
237   lambda[t] <- Ntot[t+1]/Ntot[t]
238 }
239
240 # Observation model
241 for (t in 1:n.occasions){
242   C[t] ~ dnorm(Ntot[t], tau.fit)
243   count[t] ~ dnorm(C[t], sd.count[t])
244
245   # Total population size
246   Ntot[t] <- N[1,t] + N[2,t]
247 }
248
249 }
250 ")
251
252
253 # Bundle data
254
255 # Number of states
256 ns <- length(unique(as.numeric(ch.new))) + 1
257
258 jags.data <- list(marr = ms.arr, n.occasions = ncol(ch.new), rel =
259 rowSums(ms.arr), ns = ns, zero = matrix(0, ncol = ns, nrow = ns), ones
260 = diag(ns), n.chick = n.chick, n.success = n.success, n.brood =
261 n.brood, n.product = n.product, count = count, sd.count = sd.count)
262
263 # Initial values
264 inits <- function(){list()}
265
266 parameters <- c("l.mean.sj", "l.mean.sa", "mean.sj", "mean.sa",
267 "mean.fec", "mean.p.success", "mean.prod", "mean.I", "mean.lambda",
268 "sigma.sj", "sigma.sa", "sigma.p.success", "sigma.prod", "sigma.fit",
269 "sigma.I", "sj", "sa", "p.success", "prod", "fec", "I", "Ntot", "N",
270 "lambda")
271
272 # MCMC settings
273 ni <- 100000
274 nt <- 10
275 nb <- 40000
276 nc <- 3
277
278 # Call JAGS from R (BRT 1 min)

```

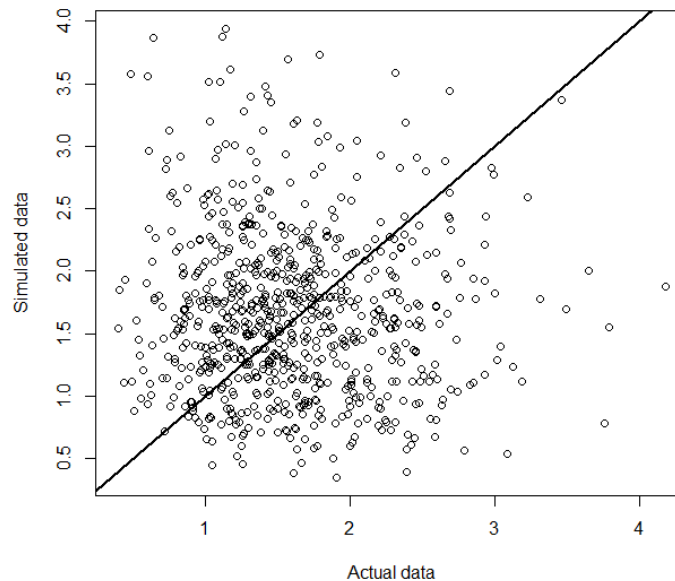
```
279 IPM <- jags(jags.data, inits, parameters, "ipm.jags", n.chains = nc,  
280 n.thin = nt, n.iter = ni, n.burnin = nb, parallel = TRUE)  
281
```


282 **Appendix 3.** Goodness-of-Fit tests for the different model components of the IPM.
283

284 We assessed the goodness-of-fit (GOF) for all model components of Bayesian IPM. For the
285 capture-recapture-recovery model we performed GOF tests using the program U-CARE (v.2.3.2,
286 Choquet et al. 2009b). For the other models (logistic regression for breeding success, normal
287 regression for productivity and population index) we conducted posterior predictive checks using
288 the Freeman-Turkey statistic. We performed a graphical assessment and computed Bayesian p-
289 values for the discrepancy statistics (Gelman et al. 2004).

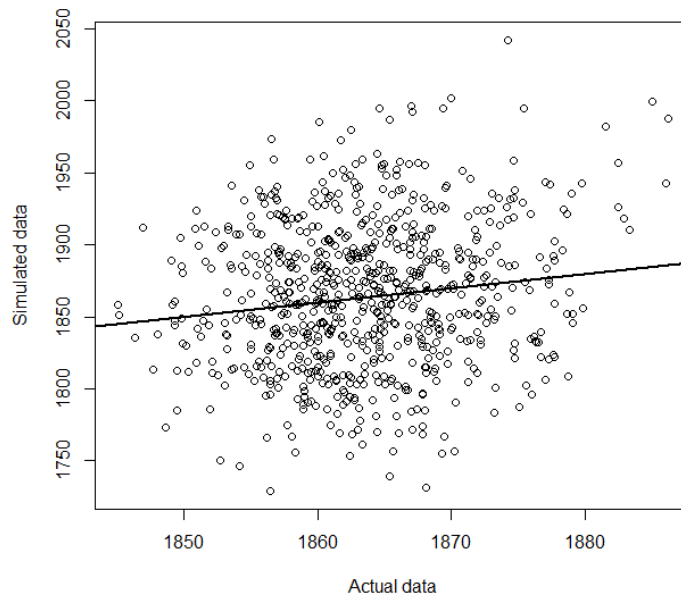
290 The GOF tests ($\chi_2 = 48.5$, $P = 0.61$) provided no indication of lack of fit for the capture-recapture-
291 recovery model. We found neither support for transience ($\chi_2 = 16.93$, $P = 0.08$) nor for trap
292 dependence ($\chi_2 = 10.47$, $P = 0.40$).

293 The next figure shows the posterior predictive check of a logistic regression to the breeding
294 success data. The solid line represents the 1:1 line. The test suggested no lack of fit between
295 observed and replicated data (Bayesian P -value = 0.53).
296



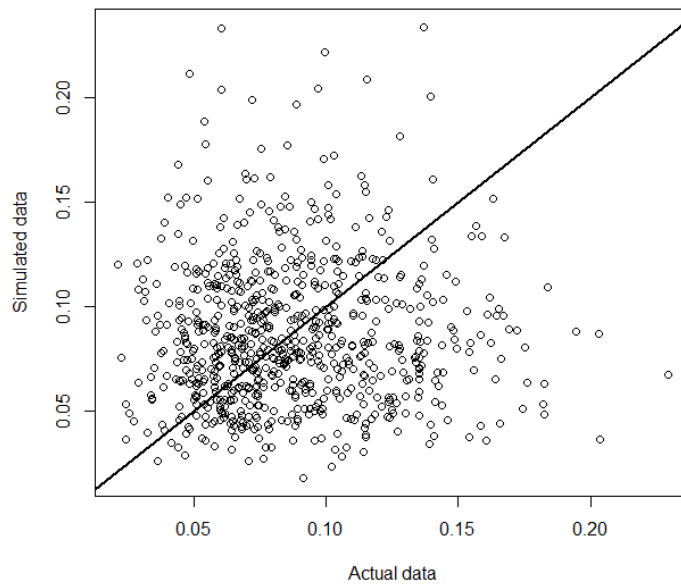
297
298

299 The next figure shows the posterior predictive check of a normal regression to the productivity
300 data. The solid line represents the 1:1 line. The test suggested no lack of fit between observed and
301 replicated data (Bayesian P -value = 0.51).
302



303
304

305 Posterior predictive check of model adequacy of a normal regression to the population index. The
 306 solid line represents the 1:1 line. The test suggested no lack of fit between observed and
 307 replicated data (Bayesian P -value = 0.50).
 308



309
310

311 Literature Cited

312 Choquet, R., Lebreton, J.D., Gimenez, O., Reboulet, A.-M. & Pradel, R. 2009b. U-CARE: utilities
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316 Chapman and Hall/CRC. London/Boca Raton.

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337 **Appendix 4.** Parameter uncertainty and sensitivity analysis

338 Breeding probability of one year-old (i.e. recruitment probability) and adult individuals could not
339 be estimated from our dataset since we lack information on the breeding state of individuals that
340 were recaptured alive. Kestrels may recruit at the age of one year but an unknown proportion of
341 individuals is likely to delay their first reproduction. We found no estimates of recruitment
342 probability for kestrels in the literature, but several studies reported the proportion of 1-year old
343 breeders in the breeding population. This value ranges from 0.15 to 0.39 (Dijkstra et al., 1990;
344 Laaksonen, Lyytinen, & Korpimäki, 2004; Schifferli, 1964; Village, 1990). A preliminary analysis
345 showed that a recruitment probability of 0.35 results in a proportion of 0.15 of 1-year old breeders
346 (CRI = [0.13, 0.17]) in our integrated population model. Thus we used 0.35 as recruitment
347 probability in our IPM. As we investigated the sink-source state of this population, we preferred a
348 conservative estimate that underestimates rather than overestimates the recruitment probability.
349 We also needed to deal with the adult breeding probability. Although non-breeding individuals
350 may be pervasive in populations (Newton, 1998), they are poorly studied. For the kestrel, there is
351 to our knowledge only a single estimate of the adult non-breeding component that originates from
352 Village (1990). Based on an intense monitoring of a breeding population, Village estimated that
353 the percentage of unpaired adult females reaches 21% (average over 6 years, Village 1990 Table
354 67). In addition, (Village, 1990) reported that around 10% of the pairs failed to lay eggs. To assess
355 the sensitivity of our model to this uncertainty, we ran integrated population models using a range
356 of different adult breeding probabilities. We considered values ranging from 1 to 0.70 assuming
357 that this range includes the true unknown value for our population.

358

359 Literature Cited

360 Dijkstra, C., Bult, A., Bijlsma, S., Daan, S., Meijer, T., Zijlstra, M., 1990. Brood Size
361 Manipulations in the Kestrel (*Falco tinnunculus*): Effects on Offspring and Parent Survival. *J.*
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364 Eurasian kestrels in a seasonally and annually fluctuating northern environment. *Evol. Ecol.* 18(3),
365 215-230.

366 Newton, I., 1998. *Population Limitation in Birds*. Academic Press, London, UK.

367 Schifferli, A., 1964. Lebensdauer, Sterblichkeit und Todesursachen beim Turmfalke *Falco*
368 *tinnunculus*. *Orn. Beob.* 61, 81-89.

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370

371 **Appendix 5.** Effects of nest types on fecundity

372 We reviewed the literature on reproduction of kestrels to investigate the effects of nest types on
373 fecundity. We only included studies reporting the fecundity as the average number of fledglings
374 per reproductive attempt and the type of nest used. From each study we recorded sample size
375 (number of clutches monitored) and study duration. We defined three categories of nest types that
376 reflect their openness. First, *nest boxes* that gather all types of nest boxes designed to fit the
377 requirements of kestrels. Second, *natural cavities* that include tree cavities, cavities in buildings,
378 more generally all nests on man-made structures and cliffs. This category includes both closed and
379 semi-closed nests, but nest descriptions were generally not precise enough to define more accurate
380 classes. Finally, *open nests* include old stick nests of birds, often of corvid species. When available,
381 we recorded clutch size, hatching success (number of chicks hatched against clutch size) and chick
382 survival (number of chicks reaching the ringing age against the number of chicks hatched). A
383 statistical meta-analysis was performed to test the effect of nest types on fecundity. We fitted a
384 Gaussian mixed model in a Bayesian framework. Fecundity was modeled as a function of nest type
385 and the variance of the population random effect was inversely proportional to the sample size and
386 the length of the study. The code of the model implemented in JAGS is available in the appendix
387 6. To quantify the effect of nest boxes in the observed population dynamics, we ran a second time
388 the integrated population model assuming absence of nest boxes by removing the effect of nest-
389 box on fecundity. We subtracted from the observed fecundity the difference of the average number
390 of fledglings between nest boxes and natural cavity and open nests, respectively. We compared the
391 resulting changes in net dispersal rate between the models. In the absence of nest boxes, kestrels
392 breed mainly in open nests in Switzerland. In a local study, Jeanmonod & Broch (2001) reported
393 that around 80% of kestrels were breeding on trees in disused nests of other species. To assess the
394 potential role of nest boxes on the population dynamics we therefore first compared fecundity
395 obtained in nest boxes and fecundity obtained in open nests. We also assessed a scenario under
396 which 80% of kestrels breed in open nests and 20% in natural cavities. These simulations all assume
397 that survival is not affected by the nest type. We discuss in appendix 7 the effect of a violation of
398 this assumption on the results.

399

400 Literature Cited

401 Jeanmonod, J. & L. Broch (2001): Suivi d'une population de Faucon crécerelle *Falco tinnunculus*
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405 (Suisse), 1999. Nos Oiseaux, suppl. 5. Nos Oiseaux, Société romande pour l'étude et la protection
406 des oiseaux, La Chaux-de-Fonds.

407 **Appendix 6.** JAGS code for the meta-analysis investigating the effect of the nest type on
408 fecundity in the Eurasian kestrel (*Falco tinnunculus*).

409

```
410 cat(file = "weighted_regression.jags", "
```

```
411   model {  
412     # Priors and constraints  
413     beta01 ~ dunif(-5, 5)  
414     beta02 ~ dunif(-5, 5)  
415     tau.eps <- pow(sigma.eps, -2)  
416     sigma.eps ~ dunif(0.001, 10)  
417  
418     for (i in 1:3){  
419       alpha[i] ~ dunif(0, 5)  
420     }  
421  
422     #Likelihood  
423     for (i in 1:n){  
424       BS[i] ~ dnorm(mu[i], tau[i])  
425       mu[i] <- alpha[Nest_type[i]]  
426       tau[i] <- pow(sigma[i], -2)  
427       sigma[i] <- exp(beta01 * Study_duration[i] +  
428                     beta02 * Sample_size[i] + eps[i])  
429       eps[i] ~ dnorm(0, tau.eps)  
430     }  
431   }  
432  
433  
434  
435  
436  
437  
438  
439  
440  
441  
442  
443  
444  
445  
446  
447  
  
448  
  
449
```

450 **Appendix 7.** Discussion of the modelling assumptions and of the effect of their violation on the
451 results.

452 The dispersal rates are highly challenging to estimate (Abadi et al., 2010) and not surprisingly
453 most of the studies assessing the source/sink state of a population do not estimate these
454 parameters (Furrer and Pasinelli, 2016). Because our data were analysed with an integrated
455 population model, it was possible to estimate the net dispersal rate. The IPM relies on
456 assumptions and it is important to assess whether the potential violation of these assumptions
457 compromise the inference. Some of the assumptions can be assessed by goodness-of-fit tests (see
458 appendix 3) but for others this is not possible. Here we discuss these latter assumptions and the
459 potential effects of their violations.

460 The IPM assumed that dispersal occurs only at age 1 year. We made this assumption because it is
461 not possible to estimate both natal and breeding dispersal given the available data. If the IPM is
462 formulated with both processes, the parameters would not be separately identifiable. This
463 assumption is reasonable given the large scale of our study area and the stronger propensity of
464 juveniles to disperse relatively to adults. Terraube et al. 2015 found that the average breeding
465 dispersal distance is 17.8 km for female and Paradis et al. (1998) reported an average breeding
466 dispersal of 14.8 km. Thus breeding dispersal occurs in average over relatively short distance
467 compare to our study area. In kestrels like in birds in general, juveniles disperse over longer
468 distance than adult (Greenwood 1980). Paradis et al. (1998) found that natal dispersal distances in
469 kestrels were roughly 3 times higher than breeding dispersal distances. Because natal dispersal is
470 much more important than breeding dispersal, we preferred to assume that only natal dispersal
471 occurs. However, the violation of this assumption has minor consequences in our case because
472 the IPM only included two age classes (1 year old and >1year old) with equal survival rates.
473 Thus, whatever the age of the dispersers, they will move from population pools where all
474 individuals have fairly similar vital rates. Pooling all individuals older than 1 year into the same
475 age class is itself a simplifying assumption. This simplification is seen frequently in models for
476 short lived birds (i.e. Robinson et al. 2014) like kestrels (breeding may start at one year, clutch
477 size of 5 eggs, life expectancy less than 10 years). Consistently with this assumption, survival
478 stabilizes after the first year of life in kestrels (Village 1990). Ignoring senescence has a minor
479 effect in our case because we sampled adults of unknown age meaning that we estimated
480 averaged productivity and survival rates relatively to the age rather than extrapolating vital rates
481 of young adult to all age classes (Robert et al. 2015). A further assumption was that the vital rates
482 did not differ among sexes. If adult survival is strongly affected by sex, the IPM may produce
483 biased estimates. However, survival of kestrels is expected to be little affected by the sex
484 (Newton 2016) and field observations are consistent with an equilibrate sex-ratio.

485 The IPM included two demographic parameters that were not estimated from our datasets, i.e. the
486 recruitment probability at one year of age and the adult breeding frequency. Values for these
487 parameters were therefore fixed in the IPM. For the recruitment probability, we used the lowest
488 known values in order to be conservative regarding the assessment of a source status. Higher

489 values of recruitment probability would result in lower values of the net dispersal rate i.e.
490 stronger emigration, corroborating inference that the population is a source. For the adult
491 breeding probability we have run a sensitivity analysis to assess how much the main results were
492 affected by the uncertainty regarding this parameter. We used different values reflecting values
493 reported in the literature (0.7, 0.8, 0.9 and 1) showing that this uncertainty did not affect the main
494 conclusion of this study (Fig. 3, A3). The lowest value that we used originated from a population
495 that is limited by nest site availability (Village 1990) which is currently not the case in our study
496 area. Thus, again we considered conservative values regarding the assessment of a source status.

497 Finally, we used simulations to investigate the effect of nest type on kestrel population dynamics.
498 In these simulations we assumed that only fecundity but not the survival of adults was affected by
499 the nest type, i.e. we assumed no covariation between survival and reproduction. Yet nest type
500 may affect both reproduction and survival. In particular nest boxes may positively affect survival
501 for the same reason they increase breeding success (i.e. lower predation risk and less exposure to
502 adverse weather events, Libois et al. 2012). To quantify the potential impact of positive
503 covariation of survival and breeding success, we ran an integrated population model under the
504 assumption that individuals breeding in natural nests suffered not only lower fecundity, but also a
505 3% and a 10% lower adult survival rate compared to individuals breeding in nest boxes. Results
506 show that the advantage of using nest boxes becomes stronger (Fig. A4). Thus our assessment
507 regarding the advantage of nest boxes on kestrel population dynamics is conservative.

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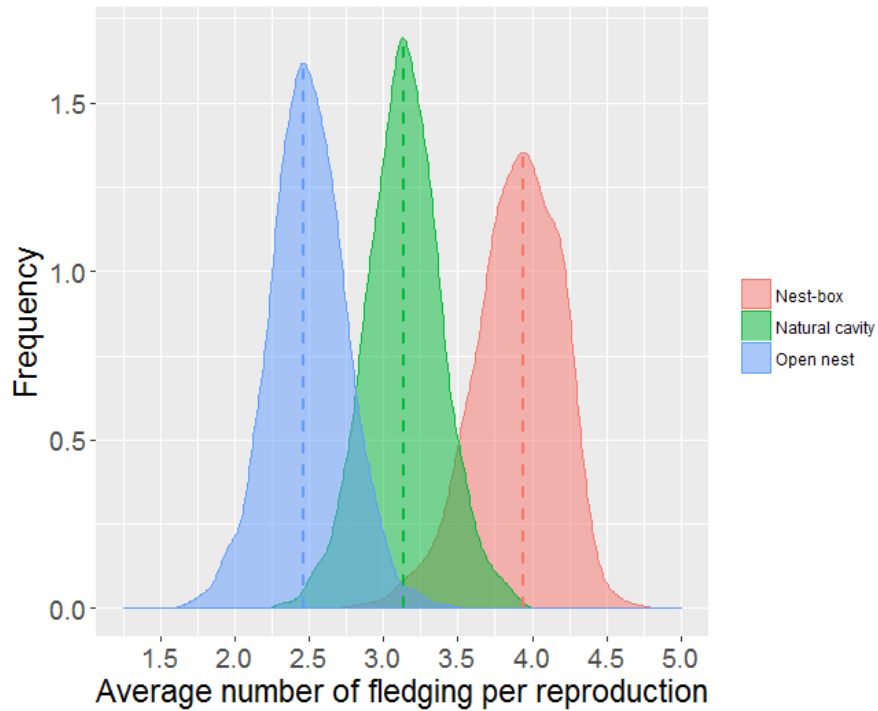
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521 **Appendix 8.** Additional figures and tables.

522 **Figure A1.** Posterior distribution of the average fecundity according to the nest type. Dashed
523 lines show the modes. Estimates are obtained from the meta-analysis on the studies presented in
524 the table A1.

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529 The probability that the fecundity in nest-boxes was higher than in natural cavities and open nests
530 was 0.96 and 1, respectively. The probability that the fecundity is higher in a natural cavity
531 compared to an open nest is 0.95.

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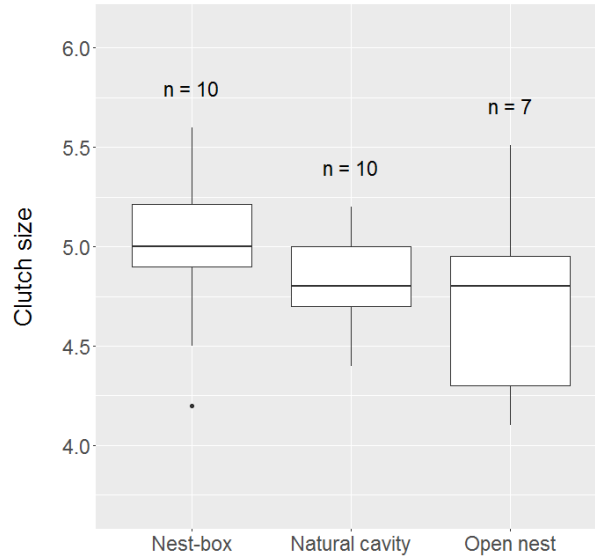
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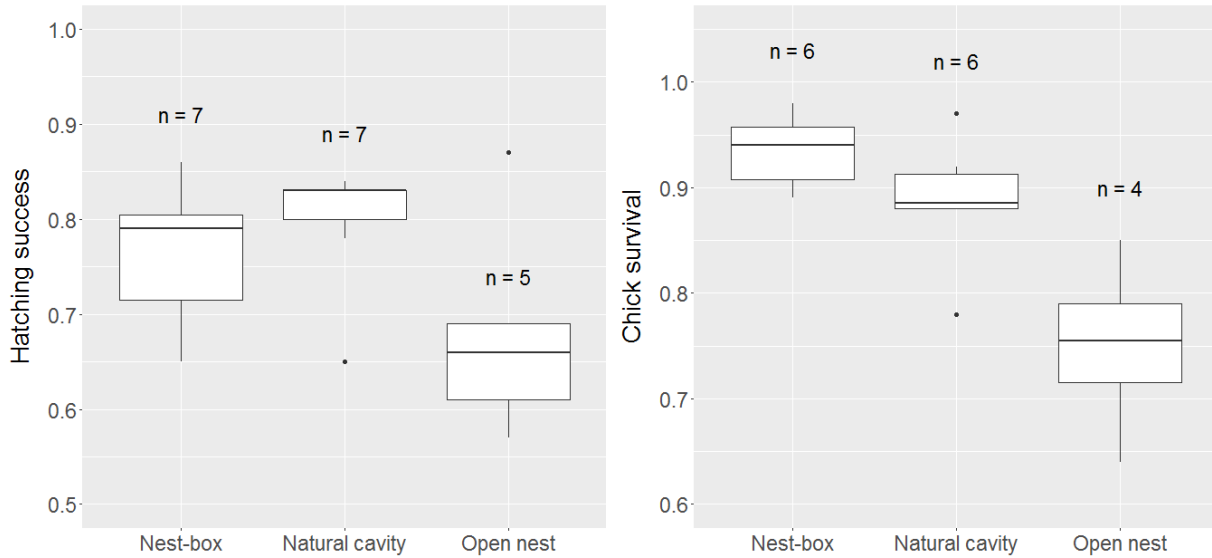
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538 **Figure A2.** Distribution of the average clutch size, hatching success and chick survival according
539 to nest type in the Eurasian kestrel (*Falco tinnunculus*). Estimates are obtained from the meta-
540 analysis on the studies presented in the table A1. The sample size, i.e. the number of populations
541 monitored for each distribution, is provided by n.



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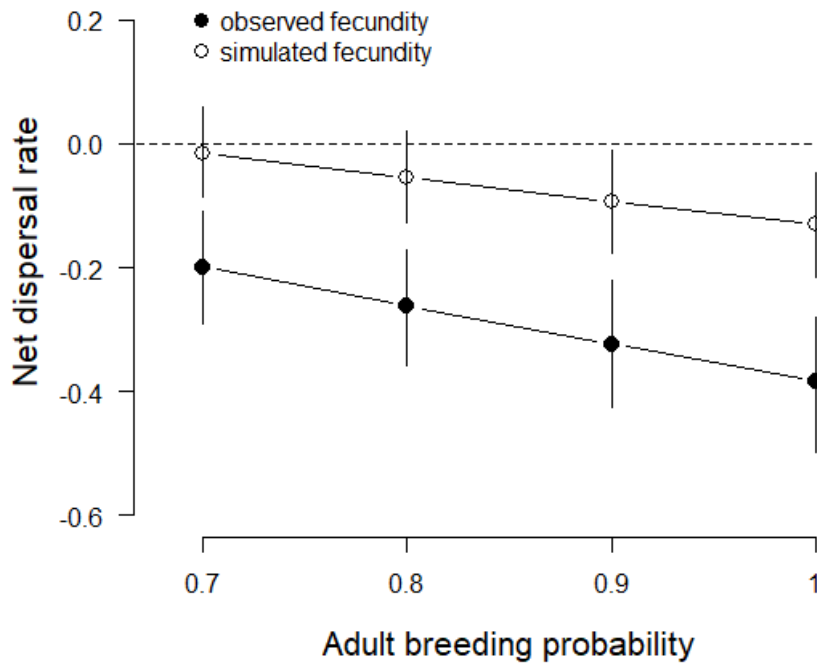
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549 **Figure A3.** Posterior means with 95% credible intervals of the average net dispersal rate over the
550 study period (2002-2016) obtained from the integrated population model according to different
551 values of adult breeding probability. Results are given considering the fecundity estimate from
552 our studied population breeding in nest boxes (filled point) and with a simulated fecundity
553 corresponding to 80% of birds breeding in open nest and 20% in natural cavity nest (appendix 5).

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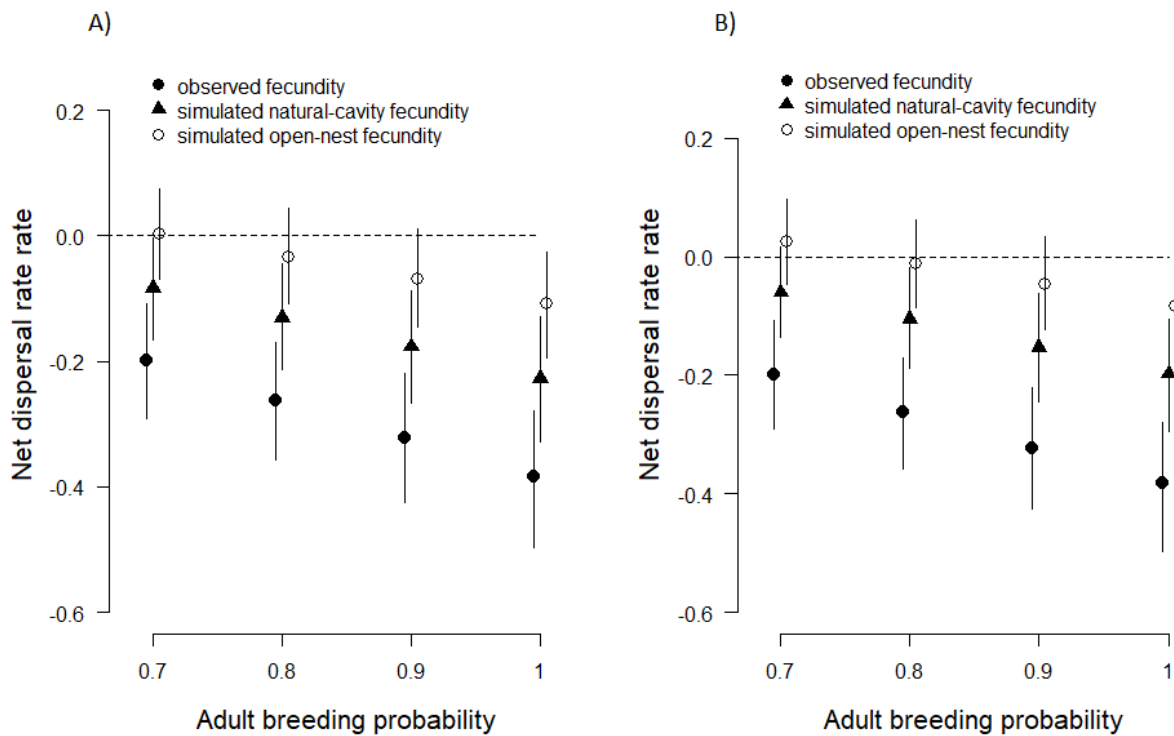
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564 **Figure A4.** Posterior means with 95% credible intervals of the average net dispersal rate over the
565 study period (2002-2016) obtained from integrated population models with different values of
566 adult breeding probability. Results are given considering the fecundity estimate from our studied
567 population breeding in nest boxes (closed dots) and with simulated fecundities assuming that all
568 kestrels either breed in natural cavities (closed triangles) or in open nests (open dots). We
569 investigated the effect of a positive covariation between reproduction and adult survival by
570 simulation. We assumed that adult survival was either 3% ($S_2=0.70$, panel A) or 10% ($S_2 = 0.65$,
571 panel B) lower when the birds used open nests for breeding compared to when they used nest
572 boxes (see Fig. 3).

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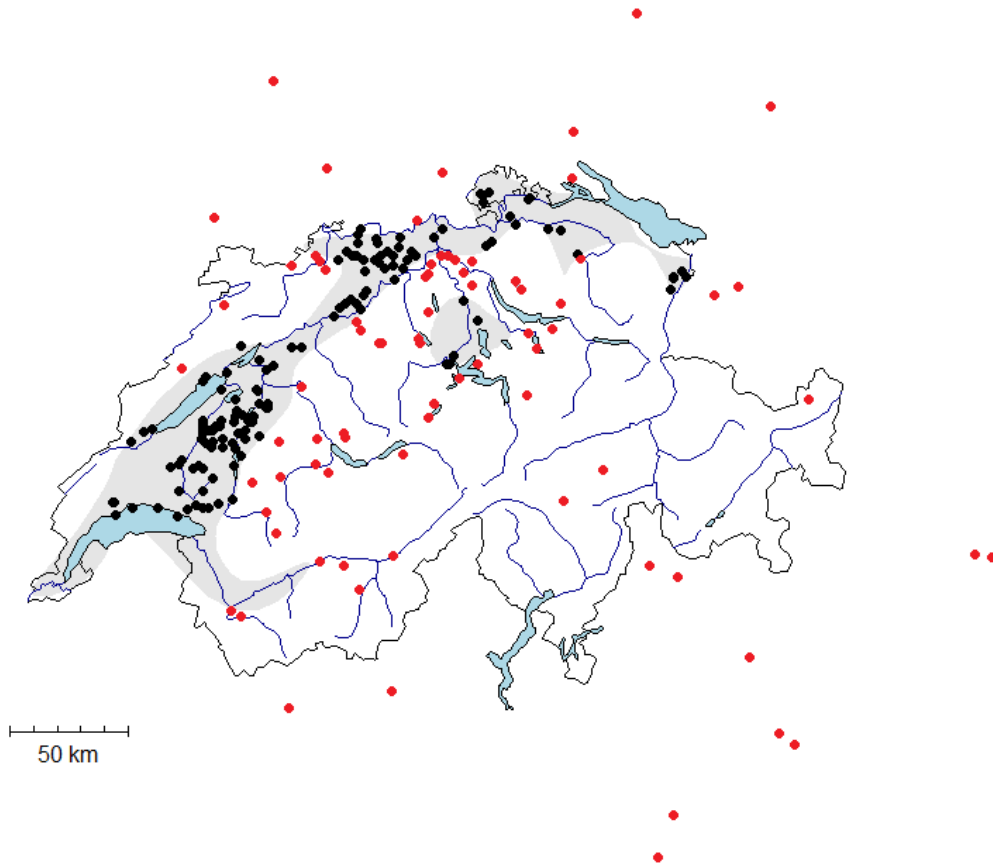
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581 **Figure A5.** Locations of recovered adult kestrels that have been ringed as nestling within the
582 study area (gray). Black dots show recoveries within the study area and red dots recoveries
583 outside the study area.



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585 To ensure that migratory movements are excluded as much as possible, we included only
586 recoveries that were obtained during the breeding period (from the 1 April to 15 August). From
587 the total number of 221 recoveries, 88 (40%) originated from outside the study area.

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594 **Table A1.** Review of studies investigating reproductive parameters of Eurasian kestrels (*Falco*
595 *tinnunculus*).

596 We only included studies reporting estimates of fecundity (defined as the average number of
597 fledglings per reproductive attempt) and the type of nest used (NB: nest-box, NC: natural cavity,
598 ON: open nest). When available, we considered hatching success (number of chicks hatched
599 against clutch size) and chick survival (number of chicks reaching the ringing age against the
600 number of chicks hatched). Sample sizes for clutch size, hatching success, chick survival and
601 fecundity are given in brackets. For some studies sample size was not provided explicitly for each
602 reproductive parameter. In this case we provided an estimated sample size and those are indicated
603 by “*”.

Nest type	Location	Study duration	Clutch size	Hatching success	Chick survival	Fecundity	Reference
NB	Spain (Extremadura)	1 (1989)	4.2 (136)	0.79 (131)	NA	3.7 (124)	Avilès et al. 2001
NB	Germany (Berlin)	3 (2002-2004)	NA	NA	NA	4.7 (30)	Kübler et al. 2005
NB	Italy (Parma)	4 (2007, 2009-2011)	5.25 (109)	0.81 (107)	0.96 (106)	4.2 (113)	Costantini et al. 2014
NB	Germany (Bielefeld)	15 (1972-1987)	5.3 (23)	0.80 (122)	0.93 (98)	4.0 (23)	Hasenclever et al. 1989
NB	Spain (Avila, Segovia)	6 (1993-1998)	5.0 (84)	NA	NA	3.7 (79)	Fargallo et al. 2001
NB	Israel	4 (2003-2006)	5.0 (101)	0.71 (103)	0.89 (91)	3.2 (124)	Charter et al. 2007a
NB	Israel (Jordan Rift Valley)	8 (1999-2006)	4.9 (31)	0.65 (32)	0.90 (26)	3.0 (37)	Charter et al. 2007b
NB	Finland (Ostrobothnia)	11 (1985-1995)	5.6 (178)	NA	NA	3.8 (180)	Valkama & Korpimäki 1999
NB	France (Côte d'or)	21 (1992-2012)	4.5 (54)	0.72 (49)	0.98 (49)	2.9 (49)	Sternna & Boileau 2013
NB	Czech Republic (Hradec Králové)	4 (1986-1989)	4.9 (224)	NA	NA	4.3 (224)	Plesnik & Dvsik 1994
NB	Germany (Berlin)	NA	NA	NA	NA	4.3 (416)	Kupko et al. (2000)
NB	Swiss	NA	5.1 (50)	0.86 (169)	0.95 (141)	4.2 (141)	Schmid 1990
NC	Scotland (Ayrshire)	8 (1978-1985)	NA	NA	NA	3.2 (136)	Riddle 1987
NC	England (Leicestershire)	7 (1981-1987)	4.4 (247)	0.65 (247*)	0.78 (175*)	2.3 (247*)	Village 1990
NC	Canary (Tenerife Island)	10 (1985-1994)	4.4 (133)	0.78 (133)	0.89 (124)	3.0 (124)	Carrillo & González-Dávila 2005
NC	Germany (Bielefeld)	15 (1972-1987)	5.2 (388)	0.83 (2013)	0.92 (1677)	4.0 (388)	Hasenclever et al. 1989
NC	Spain (Avila, Segovia)	6 (1993-1998)	4.9 (21)	NA	NA	2.4 (26)	Fargallo et al. 2001
NC	Iran (Golestan)	3 (2014-2016)	5.0 (32)	0.84 (30*)	0.88 (30*)	3.7 (30*)	Anushiravania & Roshanb 2017
NC	France (Côte d'or)	8 (1973-1980)	4.7 (132)	NA	NA	3.3 (143)	Bonin & Strenna 1986
NC	France (Côte d'or)	21 (1992-2012)	4.7 (40)	0.83 (37)	0.97 (35)	3.8 (35)	Sternna & Boileau 2013
NC	Italy (Roma)	4 (1995-1998)	NA	NA	NA	3.1 (83)	Salvati et al. 1999
NC	France (Limousin)	3 (1976-1978)	4.7 (25)	0.83 (25)	NA	3.3 (39)	Nore 1979
NC	Germany (München)	2 (1967-1968)	NA	NA	NA	2.1 (22)	Kurth (1970)
NC	Swiss	NA	5.1 (55)	0.82 (94)	0.88 (50)	3.6 (50)	Schmid 1990
NC	Austria (Vienna)	5 (2010-2014)	5.0 (35)	NA	NA	3.0 (35)	Kreiderits et al. 2016
ON	Scotland (Ayrshire)	8 (1978-1985)	NA	NA	NA	2.6 (46)	Riddle 1987
ON	Scotland (Eskdalemuir)	4 (1976-1979)	5.0 (120)	0.61 (130)	0.85 (89)	2.5 (134)	Village 1986
ON	Germany (Bielefeld)	15 (1972-1987)	4.3 (28)	0.87 (121)	0.77 (105)	2.9 (28)	Hasenclever et al. 1989
ON	Spain (Avila, Segovia)	6 (1993-1998)	4.8 (10)	NA	NA	2.8 (11)	Fargallo et al. 2001
ON	Israel (Jordan Rift Valley)	8 (1999-2006)	4.1 (32)	0.57 (34)	0.74 (39)	2.1 (56)	Charter et al. 2007b

ON	Finland (Ostrobothnia)	6 (1977-1982)	NA	NA	NA	3.3 (79)	Korpimäki & Norrdahl 1991
ON	France (Limousin)	3 (1976-1978)	4.9 (15)	0.69 (15)	NA	2.4 (20)	Nore 1979
ON	Germany (Brandenburg)	6 (1941-1944, 1950-1951)	NA	NA	NA	1.9 (35)	Wendland 1953
ON	Germany (Schleswig Holstein)	4 (1968-1971)	5.5 (41)	NA	NA	2.5 (60)	Zieseimer 1973
ON	Swiss	NA	4.3 (93)	0.66 (93)	0.64 (65)	1.8 (65)	Schmid 1990