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## **A new method to determine bird and bat fatality at wind energy turbines from carcass searches**

Korner-Nievergelt, F ; Korner-Nievergelt, P ; Behr, O ; Niermann, I ; Brinkmann, R ; Hellriegel, B

**Abstract:** Wind energy is of increasing importance for a sustainable energy supply worldwide. At the same time, concerns about the number of birds and bats being killed at wind turbines have been growing. In this situation, methods for a reliable estimation of bird and bat fatality numbers are needed. To obtain an unbiased estimate of the number of fatalities from fatality searches, the probability to detect the carcass of an animal being killed at a turbine has to be assessed by considering carcass persistence rate, searcher efficiency and the probability that a killed animal falls into a searched area. Here, we describe a new formula to determine the detection probability of birds or bats that are killed at wind turbines and which can estimate the number of fatalities from the number of carcasses found. The formula was developed to analyse a large data set of bats killed at wind turbines in Germany. In simulations, we compared it to three other formulas used in this context. Our new formula seems to have unbiased results when searcher efficiency and carcass removal rate are constant over time. When searcher efficiency or carcass removal rate varied with time, all four formulas showed a similar bias. These comparative results can be used to choose between methods depending on the quality of information available. Our estimator can, for instance, be adapted to different situations including temporal changes of searcher efficiency or carcass removal rate because it is based on an explicit process model.

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A new method to determine bird and bat fatality at wind  
energy turbines from carcass searches

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probability, formula, estimator

1

## 2 **Abstract**

3 Wind energy is of increasing importance for a sustainable energy supply worldwide. At the  
4 same time, concerns have been growing about the number of birds and bats being killed at  
5 wind turbines. In this situation, methods for a reliable estimation of bird and bat fatality  
6 numbers are needed. To obtain an unbiased estimate of the number of fatalities from fatality  
7 searches the probability to detect the carcass of an animal being killed at a turbine has to be  
8 assessed by considering carcass persistence rate, searcher efficiency, and the probability that a  
9 killed animal falls into a searched area. Here, we describe a new formula to determine the  
10 detection probability of birds or bats that are killed at wind turbines and to estimate the  
11 number of fatalities from the number of carcasses found. The formula was developed to  
12 analyse a large data set of bats killed at wind turbines in Germany. In simulations, we  
13 compared it to three other formulas used in this context. Our new formula seems to have  
14 unbiased results when searcher efficiency and carcass removal rate are constant over time.  
15 When searcher efficiency or carcass removal rate varied with time all four formulas showed a  
16 similar bias. These comparative results can be used to choose between methods depending on  
17 the (quality of) information available. Our estimator can, for instance, be adapted to different  
18 situations including temporal changes of searcher efficiency or carcass removal rate because it  
19 is based on an explicit process model.

20

## 21 **Introduction**

22 Wind energy is showing a rapid growth and can help to avoid the ecological and health  
23 problems of fossil and nuclear energy production (Holdren & Smith 2000). At the same time,  
24 concerns have been growing about birds and bats being killed at wind energy facilities and  
25 possible ecological (e.g. de Lucas et al. 2007, Arnett et al. 2008) and economic (Boyles et al.  
26 2011) consequences. In this situation, methods for a reliable estimation of bird and bat fatality  
27 numbers are needed that are simple enough to qualify for a broad use. In order to reliably  
28 estimate the number of fatalities at wind turbines from the number of carcasses detected one  
29 has to correct for imperfect detection ("searcher efficiency"), for carcass removal, and, if  
30 necessary, for incompletely searched area. To do so, a model is needed that reflects the  
31 important steps of the actual processes as well as possible sources of imprecision.

32 The key parameter in estimating bird and bat fatalities is the probability that an animal being  
33 killed is found by a searcher (detection probability  $p$ ). On the one hand, this probability  
34 depends on the distribution of the carcasses in the area beneath a wind turbine and on the

1 fraction of this area that can be searched, i.e. the proportion of carcasses lying in the area  
2 searched ( $a$ ). On the other hand, detection probability  $p$  is influenced by the carcass  
3 persistence probability ( $s$ ), i.e. the probability that a carcass does not disappear within 24  
4 hours (due to removal e.g. by scavengers), and the searcher efficiency ( $f$ ), i.e. the probability  
5 that a carcass that has fallen in the area searched and has not been removed is found by a  
6 searcher. Thus, the probability that an animal killed is also found can be determined as the  
7 product of  $a$  and a function  $g$  which depends on  $s$  and  $f$ :  $a * g(s,f)$ . For simplicity, we will  
8 assume here that 100 % of the area beneath a wind turbine is searched ( $a = 1$ ), so that the  
9 detection probability is  $p = g(s,f)$ . A simple example for function  $g$  is the product of carcass  
10 persistence probability and searcher efficiency,  $p = f * s$ . While this equation includes two  
11 very important factors, it does not take into account that carcasses that have been overlooked  
12 may be found during a later search. Consequently, the number of fatalities will be  
13 overestimated particularly when searcher efficiency is low and persistence time is high. More  
14 sophisticated estimators have been developed to account for repeated searches (e.g. Erickson  
15 et al. 2004, Huso 2010). In an extensive simulation study Huso (2010) showed that her  
16 estimator is more reliable than two commonly used estimators (Johnson et al. 2003, Kerns &  
17 Kerlinger 2004). These simulations also showed that her estimator works well for the North  
18 American situations where carcass persistence times normally are long (on average 32 d,  
19 Arnett et al. 2009) and usually search intervals of more than 14 days are used. However, for  
20 Central European situations with short persistence times (average 4.5 d, Niermann et al. 2011)  
21 and short search intervals (usually 1 -7 days) her estimator tends to overestimate the number  
22 of fatalities (Huso 2010). Therefore, we have developed a new formula to estimate the  
23 detection probability that allows for a detection of carcasses during repeated searches, and  
24 that is also reliable for central European situations. Our estimator is based on a conceptually  
25 different model than the one used by Johnson et al. (2003), Erickson et al. (2004) and Kerns  
26 & Kerlinger (2004) or the one used by Huso (2010). Our estimator is a more general  
27 formulation of the conceptual model used by Baerwald and Barclay (2009, see methods).  
28 An important advantage of our approach is that the formula can be adapted to different  
29 distributions of searcher efficiency or carcass removal rates. This results from the fact that it  
30 is based on an explicit model of the carcass removal and search processes. Searcher efficiency  
31 depends on the ability of a searcher to detect a carcass. This efficiency can be assumed to be  
32 approximately constant over time (i.e. with the number of searches) on uniform and bare  
33 ground. However, on structured ground some of the carcasses might be much more difficult  
34 to detect than others (Arnett 2006). As a result, carcasses that are easy to detect are more

1 likely to be found during the first search, whereas hidden carcasses will be more likely to  
2 remain on the plot. Searcher efficiency for a cohort of carcasses will, hence, decrease in  
3 repeated searches. A modification of our formula accounts for such a decreasing searcher  
4 efficiency in repeated searches.

5 We assessed the bias and precision of our new formula for the estimation of bat or bird  
6 fatalities in a simulation study. We compared the results obtained with our formula to that of  
7 three different approaches to model carcass detection. The other approaches were (1) the  
8 above-mentioned simple formula  $p = f * s^*$ , where  $s^*$  is the remaining proportion of carcasses  
9 of animals that were killed during one search interval (see below) (2) the formula of Erickson  
10 et al. (2004) that is one of the latest versions of the earlier estimators before the publication of  
11 Huso (2010), and (3) the formula of Huso (2010).

12 Simulation results were also compared with the uncorrected raw number of carcasses found  
13 ( $C$ ). Using the carcass count as an estimate for the number of animals killed ( $\hat{N}$ ), i.e.  $\hat{N} = C$ ,  
14 or just correcting it in a simple way, e.g.  $\hat{N} = C/(f*s^*)$  is still common practice despite the  
15 obvious shortcomings (Smallwood & Karas 2009, Dulac 2010).

16 In summary, we suggest a new formula to estimate bat or bird mortality at wind turbines and  
17 analyse differences in bias and precision of five methods when used in different situations.  
18 The new estimator is based on an explicit model of the processes and can be adapted to  
19 specific situations when needed. Our goal is to help in deciding which method should  
20 advantageously be used in which context.

21

## 22 **Methods**

### 23 *The formula*

24 The formula we developed is based on an explicit model of two processes: the removal by  
25 scavengers or decay, and the carcass search. The basic formula assumes that a mean number  
26 of  $\bar{m}$  individuals are killed per day, that the carcasses of these killed animals are removed (by  
27 scavengers, decay etc.) at a constant probability ( $1-s$ ; i.e.,  $s$  = daily persistence probability),  
28 and that the searcher efficiency is constant over time and similar for all carcasses. Variations  
29 of the formula can account for non-constancy in persistence time and/or searcher efficiency  
30 (see below). Searches are conducted at regular intervals of  $d$  days. During each search  
31 carcasses are found with searcher efficiency  $f$  and are removed from the plot. Based on these  
32 assumptions the number of carcasses found can be calculated (see Appendix, Table 1):

33

$$C = \bar{m}f \left( s \frac{1-s^d}{1-s} \right) \left( \sum_{i=0}^{n-1} (n-i) [(1-f)s^d]^i \right)$$

$C$  is the total number of carcasses found during  $n$  searches conducted at intervals of  $d$  days, given an average number of  $\bar{m}$  animals killed per night, a searcher efficiency  $f$ , and a carcass persistence rate  $s$ . If we divide the number of detected carcasses by the total number of animals killed ( $\bar{m} nd$ ), we obtain an estimate for the probability  $p$  of finding an animal that is killed at a wind energy turbine:

$$\hat{p} = \frac{C}{\bar{m}nd}$$

If the above formula for  $C$  is inserted in this formula,  $\bar{m}$  cancels out. This makes the detection probability  $\hat{p}$  independent of the number of killed animals:

$$\hat{p} = \frac{f \left( s \frac{1-s^d}{1-s} \right) \left( \sum_{i=0}^{n-1} (n-i) [(1-f)s^d]^i \right)}{nd} \quad (1)$$

The formula assumes that  $f$  and  $s$  are constant over time (see results of the simulation study) and that these two parameters do not differ between individual carcasses (see Discussion). Baerwald and Barclay (2009) used a similar formula as the one presented here. In their formula a carcass that is not found during the first search can also be found during the second search but not thereafter. In contrast, our formula allows that such a carcass can be found at any subsequent search. The present formula may, therefore, be seen as a generalization of the method proposed by Baerwald and Barclay (2009).

*Simulation study to assess the performance of the new formula in comparison with other formulas*

To assess the performance of the new formula we simulated data sets and subsequently used five different estimators for the number of animals killed. The simplest estimator used the number of carcasses found as a measure of mortality:  $\hat{N} = \sum_{i=1}^n c_i$  where  $c_i$  equals the number of carcasses found during the  $i$ -th search. All other estimators include a formula to estimate the probability  $p$  to detect a killed animal. For simplicity, we here divide the number of found

carcasses by  $\hat{p}$  to obtain an estimate of the number of killed animals:  $\hat{N} = \frac{\sum_{i=1}^n c_i}{\hat{p}}$ . We present in the Appendix a method to obtain a credible interval for this estimate.

1

2 The four formulas for the detection probability were:

3 1) The simple formula  $\hat{p} = f s^*$ , where  $s^* = \frac{1}{d} \sum_{i=1}^d s^{(d-i+1)}$  is the proportion of carcasses that

4 died in the time interval  $]t-d, t]$  and remained until the search at time  $t$ , and  $f$  is the searcher  
5 efficiency, i.e. the proportion of carcasses present during the search that are found by the  
6 searcher. This formula ignores carcasses that were overlooked by the searchers. i.e. it assumes  
7 that all remaining carcasses have a probability of zero to be detected during further searches.

8 2) Our formula in two versions, namely in its basic version as presented above (1) as well as  
9 in an adapted version that accounts for decreasing searcher efficiency with the number of  
10 searches:

$$\hat{p} = \frac{Af + \sum_{x=2}^n Af \left[ 1 + ks^d(1-f) + \sum_{j=1}^{x-1} \left( k^{x-j} s^{(x-j)d} \prod_{i=0}^{x-j-1} (1-fk^i) \right) \right]}{nd} \quad (2)$$

12

13 where  $A = s \frac{1-s^d}{1-s}$  and  $k$  is the factor by which the searcher efficiency decreases with each  
14 search.

15

16 3) The formula suggested by Erickson et al. (2004):

$$\hat{p} = \frac{\bar{f}}{d} \left[ \frac{e^{\frac{d}{\bar{t}}} - 1}{e^{\frac{d}{\bar{t}}} - 1 + f} \right],$$

18 where  $\bar{t}$  is the mean persistence time of a carcass. This parameter is related to the persistence

19 probability  $s$  with  $\bar{t} = \frac{1}{-\ln(s)}$ .

20 4) A formula recently developed by Huso (2010) and applied by Arnett et al. (2009):

$$\hat{p} = fkr = fk \frac{\bar{t} \left( 1 - e^{-d^*/\bar{t}} \right)}{d^*}$$

22 where  $f$  is the searcher's efficiency,  $d^* = \min(d, \tilde{d})$ ,  $\tilde{d} = -\log(0.01) * \bar{t}$ , and

23  $k = \min(1, \tilde{d} / d)$ . Here,  $r$  is the proportion of animals killed during  $d$  nights which are still

24 there at the end of the investigation period.  $k$  is either 1 or the ratio between the time until

25 99% of the carcasses have disappeared and  $d$ .

26



1 We simulated data given different scenarios (see below) and applied the five estimators to  
2 obtain an estimate of the number of killed animals from the number of carcasses found. For  
3 every simulated data set we calculated the relative error of the estimates by dividing the  
4 difference between estimated and true number of animals killed by the true number:

$$5 \text{ relative error of estimate} = (\hat{N} - N) / N$$

6

7 The following protocol was used to simulate data:

- 8 1. For  $n*d$  days, the true number of killed animals per day  $m_t$  was drawn from a Poisson-  
9 distribution with expected value  $\bar{m}$ .  $\bar{m}$  was either held constant or was proportional to  
10 empirical acoustic bat activity data taken from Behr et al. (2011).
- 11 2. The number of carcasses that have not been removed during the first day,  $N_1$ , was drawn  
12 from a binomial distribution  $N_1 \sim \text{binom}(m_1, s)$ .
- 13 2. The number of carcasses present ( $N_t$ ) at day  $t = 2$  to  $t = I$  was simulated autoregressively as  
14 the sum of two binomial processes: those animals that were killed before day  $t$  and have not  
15 been removed ( $l_t$ ) and those that were killed during day  $t$  and were not removed during that  
16 day ( $k_t$ ):  $N_t = l_t + k_t$  with  $l_t \sim \text{binom}(N_{t-1}, s)$  and  $k_t \sim \text{binom}(m_t, s)$
- 17 3. At intervals of  $d$  days virtual searches were performed. For each search day, we subtracted  
18 from  $N_t$  the number of carcasses found and removed by a searcher:  $N_t^* = N_t - c_i$  with  $c_i \sim$   
19  $\text{binom}(N_t, f)$ .  $N_t$  was then replaced by  $N_t^*$ .
- 20 4. Steps 2 and 3 were repeated until  $t$  reached the end of the investigation period ( $t = I$ ).

21

22 For scenarios with variable persistence probabilities  $s$  or variable searcher efficiencies  $f$  we  
23 kept track of the individual cohorts (animals killed on the same day) during step 2 to 4. In all  
24 simulations, the number of carcasses was zero at the beginning of the study in order to  
25 exclude effects of the initial number of carcasses on the bias estimates. In field studies, this  
26 effect can be reduced by clean-out searches at the beginning of the study and by discarding  
27 old carcasses during the first days of the study.

28 Data were simulated in order to estimate the bias in the different formulas and to assess their  
29 robustness against violations of the assumptions: First, the bias of the five estimators was  
30 assessed for data that met all assumptions made by our new basic formula (1), i.e. constant  
31 persistence probability as well as constant and independent searcher efficiency. Based on  
32 these assumptions, 12 different scenarios were simulated by using constant or variable  
33 mortality rates (for the constant case:  $\bar{m} = 0.01$ , for the variable case:  $m_t$  proportional to  
34 empirical acoustic bat activity with an average of 0.01), short or high average carcass

1 persistence times ( $\bar{\tau} = 3$  or  $\bar{\tau} = 30$ ) and three different search intervals ( $d = 1, 7, 14$ ).  
2 Searcher efficiency  $f$  was set to 0.8 and the study period to  $I = 100$  days. Secondly, we  
3 assessed the robustness of the basic formula against violation of the assumption of constant  
4 persistence probability. The little empirical data available on carcass persistence times suggest  
5 that persistence time might generally increase with exposure time of carcasses (e.g. American  
6 crows and House sparrows in North America, Ward et al. 2006; Guillemots in Alaska, Van  
7 Pelt & Piatt 1995; bats and mice, own data in electronic supplement). Though, these own data  
8 (electronic supplement) and those of Erickson et al. (2004) show that this increase in  
9 persistence time with exposure time might be negligible. To account for the scarce knowledge  
10 about temporal variability in carcass persistence times, we simulated data once with  
11 decreasing and once with increasing persistence probabilities over time for the six scenarios  
12 described above with constant  $m_t$ . Virtual carcass persistence times were simulated as random  
13 draws from a Weibull distribution with  $\bar{\tau} = 3$  or 30 and shape parameter 0.7 for increasing  
14 and 1.3 for decreasing persistence probability (see electronic supplement). Third, robustness  
15 against variation of searcher efficiency was tested using nine scenarios: the average  
16 persistence time was set to 4.5 days, the search interval was  $d = 1, 7, \text{ or } 14$ , and searcher  
17 efficiency was constant  $f = 0.5, 0.8$ , or decreased per carcass with the number of searches  $i$ :  
18  $f(i) = 0.8 * 0.25^{(i-1)}$ . For these simulations we also used our adapted formula (2) that takes into  
19 account a decrease in searcher efficiency. The range of parameter values that was used was  
20 inspired by studies on bat collisions in Germany (Brinkmann et al. 2011) and North America  
21 (Arnett et al. 2009).

22 A last set of simulations was carried out to assess the maximally possible precision that can  
23 be obtained when estimating the number of fatalities based on carcass searches. Here, we  
24 assumed that all parameters are constant in time. In different simulation runs we varied  
25 average mortality rates ( $\bar{m}$  from 0.01 to 1), and searcher efficiency ( $f$  from 0.05 to 0.95).  
26 Hundred scenarios were produced that differed in the number of carcasses found and in the  
27 detection probability for carcasses. For each scenario, the standard deviation of the relative  
28 error from 1000 replicates was used as a measure for minimal uncertainty (i.e. maximal  
29 precision).

30 In field data, several additional factors will increase uncertainty, such as a clumped temporal  
31 distribution of fatalities (i.e. a non-constant mortality rate) or an uncertainty in the estimated  
32 searcher efficiency and persistence probability. The latter two were assumed to be known in  
33 our simulations but actually have to be estimated from separate experiments using specific  
34 methods. Therefore, the standard deviations presented here have to be interpreted as a

1 minimal possible uncertainty given the number of carcasses found and the specific detection  
2 probability.

3 Due to the large variety in methods applied to estimate searcher efficiency and carcass  
4 removal rates, the exploration of bias and precision in these estimates is beyond the topic of  
5 this paper. However, we present a worked example in the Appendix that shows how to  
6 combine the uncertainty of the estimated searcher efficiency and carcass persistence  
7 probability with the uncertainty that is inherent to the observation process.

8 The simulations were done in R 2.12.0 (R Development Core Team 2010). The R-code for  
9 the simulations can be obtained from the authors upon request.

10

## 11 **Results**

12 The data simulation generally showed that the proportion of simulated data sets with zero  
13 carcasses found (i.e. no single carcass was found during the whole study period) reached up to  
14 40 % when assuming a true average of 10 animals killed during the 100 days of virtual study  
15 period (Fig. 1). The proportion increased with increasing search interval, with decreasing  
16 persistence time, and when mortality rate varied over time. The 95 % range of the relative  
17 errors strongly correlated with the proportion of zero counts among the data sets and they  
18 were similar between the different estimators.

19 The **uncorrected count** consistently underestimated the number of fatalities in all scenarios  
20 (Fig. 1, 2). The **simple formula** produced an overestimation with searcher efficiency kept  
21 constant over time for short search intervals ( $d = 1$ ) and with long persistence times (Fig. 1).  
22 When searcher efficiency decreased with the number of searches the simple formula appeared  
23 to perform well, at least for an average persistence time of 4.5 days and search intervals of 1,  
24 7 or 14 days (Fig. 2, right panel).

25 The **new formula presented here** appeared to be unbiased for all scenarios with constant  
26 parameters and robust towards a decrease of removal probability with time (Fig 1). When  
27 removal probability increased over time the formula produced an underestimation of the  
28 number of fatalities, especially with short persistence times and long search intervals. The  
29 size of this underestimation was similar to the underestimation by the other three formulas.  
30 When searcher efficiency decreased over time the basic version of our new formula produced  
31 a slight underestimation for short search intervals (Fig. 2). However, this bias was reduced  
32 when the adapted formula was used (Fig. 2).

33 The **formula of Erickson et al. (2004)** slightly underestimated the number of fatalities when  
34 persistence times were short (Fig. 1), but appeared to produce unbiased results for long

1 persistence times. This formula was rather robust towards temporal variation in removal  
2 probabilities. However, for short average persistence times and increasing removal  
3 probabilities, this formula produced an underestimation, too.

4 The **formula of Huso (2010)** tended to overestimate the number of fatalities for short search  
5 intervals and long persistence times and constant low searcher efficiency (Fig. 1, 2). This  
6 formula was quite robust when removal probabilities decreased over time and it showed a  
7 similar negative bias as our formula when persistence times were short, removal probability  
8 increased and search interval was large. The Huso (2010) formula seemed to be robust against  
9 decreasing searcher efficiency (Fig. 2).

10 The standard deviations of the relative error (hereafter called "uncertainty") were substantially  
11 smaller when the uncorrected counts were used as estimator than when a formula was used  
12 that accounted for detection probability. However, uncorrected counts were strongly  
13 negatively biased. Therefore, we do not show the uncertainty of this method here. The  
14 uncertainty and its correlation with the number of carcasses found and with the detection  
15 probability did not differ substantially between the four formulas (simple formula, new  
16 formula presented here, Erickson et al. 2004, and Huso 2010). Therefore, we present only the  
17 results for our formula. The uncertainty decreased with the number of carcasses found and  
18 with increasing detection probability (Fig. 3). When less than ten carcasses were found the  
19 uncertainty increased dramatically, especially when detection probability was low.

## 22 **Discussion**

23 We present a new estimator for the number of bats or birds killed at wind turbines from the  
24 number of carcasses found in fatality searches. Similar to previously published approaches,  
25 our new method accounts for the bias resulting from carcass removal by predators or decay  
26 and from imperfect detection. In a simulation study we compared our estimator with four  
27 existing ones. All five estimators assume that 100 % of the area beneath a wind turbine is  
28 being searched. When only parts of the area can be searched, a correction is necessary that  
29 takes into account the distribution of carcasses beneath a turbine (Hull & Muir 2010, Arnett et  
30 al. 2009, and Niermann et al. 2011).

31 The five estimators we compared differed with respect to bias. If the number of carcasses  
32 found was used directly as an estimator of the number of fatalities, this number was, of  
33 course, consistently underestimated. This method works best with high detection  
34 probabilities. It has the advantage to be cheap and fast, because no experiments to assess

1 searcher efficiency ( $f$ ) and carcass persistence probability ( $s$ ) are necessary. However, it only  
2 gives a minimum number of dead animals and under most conditions the estimated number of  
3 fatalities will only be very weakly correlated with the real number of animals being killed.  
4 Not surprisingly, the number of fatalities can be estimated more accurately when the detection  
5 probability is accounted for. Even using the simple formula  $p = f*s$  reduced the bias  
6 considerably. However, this method overestimated the number of fatalities when search  
7 intervals were short or carcass persistence rates were high (Fig. 1, 2). That is because the  
8 formula ignores the carcasses that were missed in a search. When searcher efficiency  
9 decreases with the number of searches the simple formula can produce fairly reliable results.  
10 Many studies on bat and bird mortality at wind turbines have used this simple formula, e.g. to  
11 estimate bird mortality with a mean search interval of 17 to > 90 days (Smallwood and Karas  
12 2009) or to assess bat mortality with weekly searches (Dulac 2010).  
13 When comparing the performance of the three more complex formulas (Erickson et al. 2004,  
14 Huso 2010, and our formula) none can be identified to be consistently superior to the others  
15 according to our simulations. The formula of Erickson et al. (2004) generally showed a slight  
16 underestimation. Our formula produced, on average, the smallest bias. When searcher  
17 efficiency decreased with the number of searches, our formula could be adapted, whereas the  
18 formula of Huso (2010) appeared to be robust towards decreasing searcher efficiency. This  
19 formula was designed to be robust when detectability is heterogeneous, as is the case when  
20 searcher efficiency decreases (see Huso 2010). It overestimated, however, the number of  
21 fatalities when searcher efficiency was low and independent of previous searches and when  
22 the search interval was short (Fig. 2). All three formulas similarly underestimated the actual  
23 number of fatalities when removal probability was high and when it increased over time.  
24 If the strength of the increase or decrease of the removal probability over time is known (or  
25 estimated from experimental data) it is possible to adapt our new formula to account for the  
26 temporal variation in removal probability. This is possible because our estimator is based on  
27 an explicit model of the removal and search process. Empirical data from bats and mice  
28 carcasses (electronic supplement, Erickson et al. 2004) or bird carcasses (Van Pelt & Piatt  
29 1995, Ward et al. 2006) suggested that removal probabilities were either constant or slightly  
30 decreasing over time. Removal rates may decrease with time because those carcasses most  
31 easily detected by scavengers are removed first, leaving only those more difficult to detect on  
32 the plot. For the same reason, searcher efficiency is often assumed to decrease with  
33 persistence time.

1 A further issue that has to be addressed in real cases is that removal probability might be  
2 lower for the first day than during subsequent days because the exposure time is on average  
3 shorter than 24 hours for the day the animal is killed. In this case, it might be necessary to  
4 include a separate persistence probability for the first day in the formula. However, for bats in  
5 central Europe it seems reasonable to assume similar carcass persistence probabilities  $s$  for the  
6 first and subsequent days: most of the bats are likely to be killed during the first half of the  
7 night (as inferred from acoustic activity measurements, Behr et al. 2011) and activity of the  
8 most common predator, the red fox *Vulpes vulpes*, peaks in the second half of the night (Ott  
9 2009).

10 All formulas presented here assume a constant search interval. In the field, searches may be  
11 performed at irregular time intervals. Different search interval patterns will affect the fatality  
12 estimate each in its own way. This strongly suggest to agree on a realistic schedule and to  
13 stick to it as closely as possible. Alternatively, the effect of a specific search interval pattern  
14 can be assed based on simulated data.

15 When the animals killed include a variety of species with different body sizes (e.g. from  
16 hummingbirds to eagles), persistence time and detectability may differ substantially between  
17 individual carcasses. Such heterogeneity in persistence time and in detectability can produce a  
18 bias in the estimated number of fatalities, as it has been described for mark-recapture models  
19 used to estimate population size (Carothers 1973; Nichols et al. 1982; Pollock and Raveling  
20 1982). Species-specific heterogeneity in persistence time and detectability can be reduced by  
21 analysing groups of similar species separately.

22 The distribution and the mean of carcass persistence times will also most likely differ  
23 substantially between different study sites because of differences in e.g. predator behaviour,  
24 temperature, and humidity. Within Germany we found carcass persistence times that varied  
25 between 1.3 and 24.5 days at 30 different wind turbines (with a mean of 4.2 days; Niermann  
26 et al. 2011). Arnett et al. (2009) report a mean persistence time of 32 days in North America.  
27 Furthermore, vegetation cover and other ground parameters (e.g. stones) differ between study  
28 sites producing heterogeneity in carcass detectability to different degrees. The search interval  
29 and study period also differ between studies depending on the time and funding available.  
30 These differences have to be accounted for when estimating fatality rates. Therefore, and  
31 based on our simulation results we suggest that there may not be a universal formula that is  
32 applicable in all situations. For each study, the most appropriate method should be chosen and  
33 our simulation study can provide an orientation for this decision.

1 We found a strong correlation of the (highest possible) precision of the estimated number of  
2 fatalities with both the number of carcasses found and with the detection probability: If less  
3 than ten carcasses were found, the (highest possible) precision in our simulation was low,  
4 suggesting that conclusions from studies where only few dead animals are detected will be  
5 very uncertain. This implies that at some sites a big search effort may be necessary to obtain  
6 estimates with acceptable precision. The number of carcasses found can be increased e.g. with  
7 shorter search intervals, a longer study period, a larger proportion of area searched, an  
8 improved visibility in the area searched, and by increasing the number of turbines included in  
9 the study. However, optimising the visibility in the area searched should be done with care  
10 because it might affect the number of fatalities by altering the habitat use by the animals.  
11 Data from different turbines and estimated searcher efficiencies from different searchers can  
12 be combined in different ways. Jones et al. (2009) suggested generalised linear models  
13 (GLM). In our extensive study we used weighted averages of searcher efficiencies per turbine  
14 with weights proportional to three visibility classes in the area searched and to the number of  
15 searches per person (Niermann et al. 2011).

16 Once the searcher efficiency and removal probabilities are estimated for a specific study, one  
17 of the formulas discussed in this article can be applied to obtain an estimate for the number of  
18 fatalities. To obtain an uncertainty measure for this estimate, several sources of uncertainties  
19 have to be included: 1) the randomness produced by the count process, 2) the uncertainty in  
20 the estimated removal probability, 3) the uncertainty in the estimate for searcher efficiency,  
21 and 4) if less than 100 % of the area beneath a wind turbine is searched, the uncertainty of the  
22 estimated proportion of killed animals that fall into a searched area. Numbers 2) to 4) were  
23 not included in our simulation studies in this article. The uncertainty in actual field data  
24 would therefore be considerably higher than in the simulated data presented here. We provide  
25 one possibility to combine the sources of uncertainty mentioned above for real data in a  
26 worked example in the Appendix.

27

28 To summarize, the new formula presented here appears to provide an unbiased estimate of the  
29 number of animals killed when searcher efficiency and removal probability are constant in  
30 time. The robustness of the new formula with respect to temporal variation in the removal  
31 probability or searcher efficiency is similar to that of other formulas published. However, in  
32 contrast to other approaches the formula presented here is based on an explicit carcass search  
33 process model that can be adapted to the specific circumstances of a field study.

34

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1 Tables

2

**Table 1. Definitions of important parameters used**

---

$d$	= search interval, i.e. number of days between two searches
$n$	= number of searches in the study
$s$	= daily persistence probability of a carcass, i.e. proportion of killed bats/birds which do not disappear (e.g. due to decay or scavengers) in 24 h
$\bar{t}$	= average persistence time of a carcass
$f$	= searcher efficiency, i.e. the proportion of bats/birds killed and not removed that are found during one search
$I$	= length of study period (days); $I = n*d$
$N$	= number of bats/birds which were killed during the study period $I$ (unknown parameter of interest)
$N_t$	= number of bats/birds which were killed during day $t$
$\bar{m}$	= average number of bats/birds killed during one day
$c_i$	= number of carcasses counted during search $i$
$C$	= $\sum_{i=1}^n c_i$ , the total number of counted carcasses
$p$	= probability that a bat/bird, which is killed during the study period $I$ , is found

---

3

4

1 Figure legends

2

3 Fig. 1. Relative errors of five different estimators for the number of fatalities in 1000  
4 simulated data sets for eight different scenarios (symbols = means, bars = range of 95 % of  
5 the relative errors). In the upper row, data were simulated with a high carcass removal rate  
6 (short average persistence time  $\bar{t} = 3$  days). In the lower row, a long persistence time of 30  
7 days was assumed. In the first column, mortality and removal rates were constant over time.  
8 In the second column, mortality rate was proportional to empirical acoustic bat activity (i.e.  
9 mortality rate varied from day to day; own data), simulating a natural distribution of bat  
10 fatalities. In the last two columns, removal rate decreased (third column) or increased (fourth  
11 column) with time. See text for details of the five different estimators. – Constant parameters:  
12 searcher efficiency  $f = 0.8$ , mean mortality rate per night  $\bar{m} = 0.1$ , study period  $I = 100$  days. -  
13 Wide grey bars (right axes): proportion of simulated data sets with zero carcasses found.

14

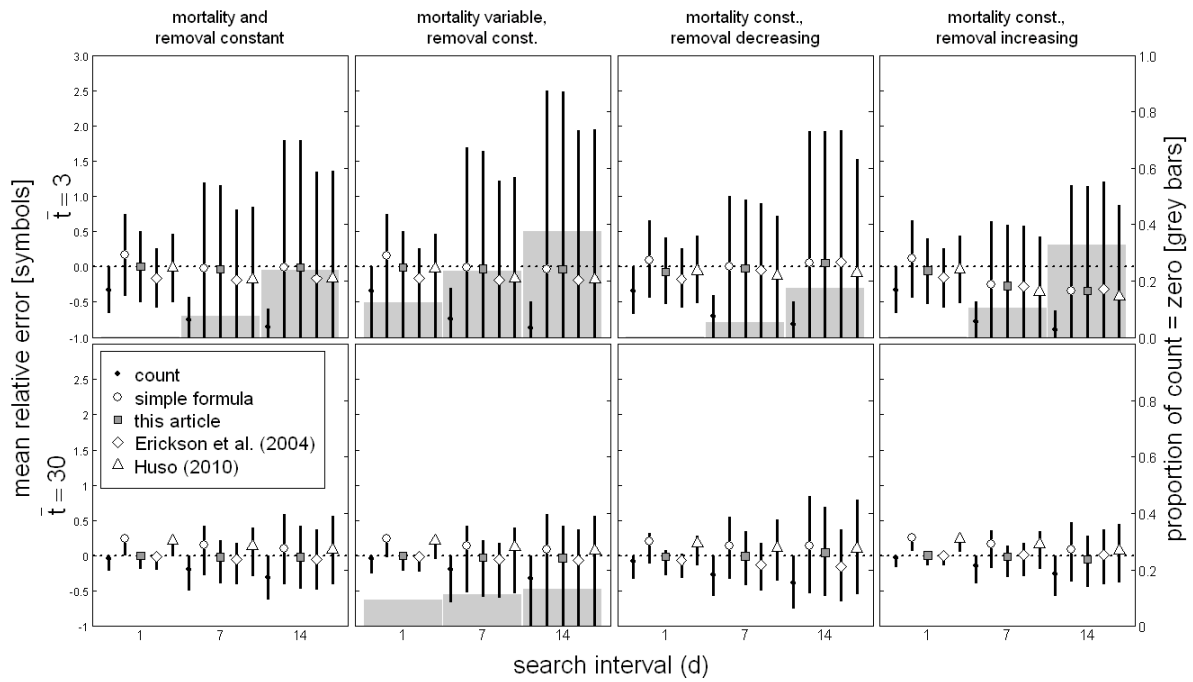
15 Fig. 2. Relative errors of six different estimators for the number of fatalities in 1000 simulated  
16 data sets for three different scenarios (symbols = means, bars = range of 95 % of the relative  
17 errors). The first and second plots show the relative errors if searcher efficiency  $f$  is low or  
18 high, respectively and constant over time. In the third plot, searcher efficiency was 0.8 during  
19 the first search and then decreased by the factor 0.25 for each subsequent search to simulate  
20 carcasses missed at the search. In addition to the five estimators presented in Fig. 1 the  
21 adaptation of our formula is shown that allows for a decrease in searcher efficiency (formula  
22 2 in the text).

23

24 Fig. 3. Highest possible precision given the number of carcasses found and the detection  
25 probability: Shown are the standard deviations of the relative errors (estimated fatalities  
26 minus true fatalities divided by true fatalities) for different numbers of carcasses found (x-  
27 axis) and for different detection probabilities (numbers), based on simulated data (see text).  
28 Only results for our formula are presented - the formulas of Huso (2010) or Erickson (2004)  
29 showed similar results. For data simulation, average persistence time was set to 30 days,  
30 searcher efficiency varied from 0.05 to 0.95, mean number of fatalities per night varied from  
31 0.01 to 1, search interval was set to 7 days and total time sampled to 100 days. Note that the  
32 standard deviations in this figure show the uncertainty induced by the variation of the  
33 Poisson-distribution of the simulated fatalities and by random effects in the search process,  
34 only. In field data, several additional factors will increase uncertainty, such as a clumped

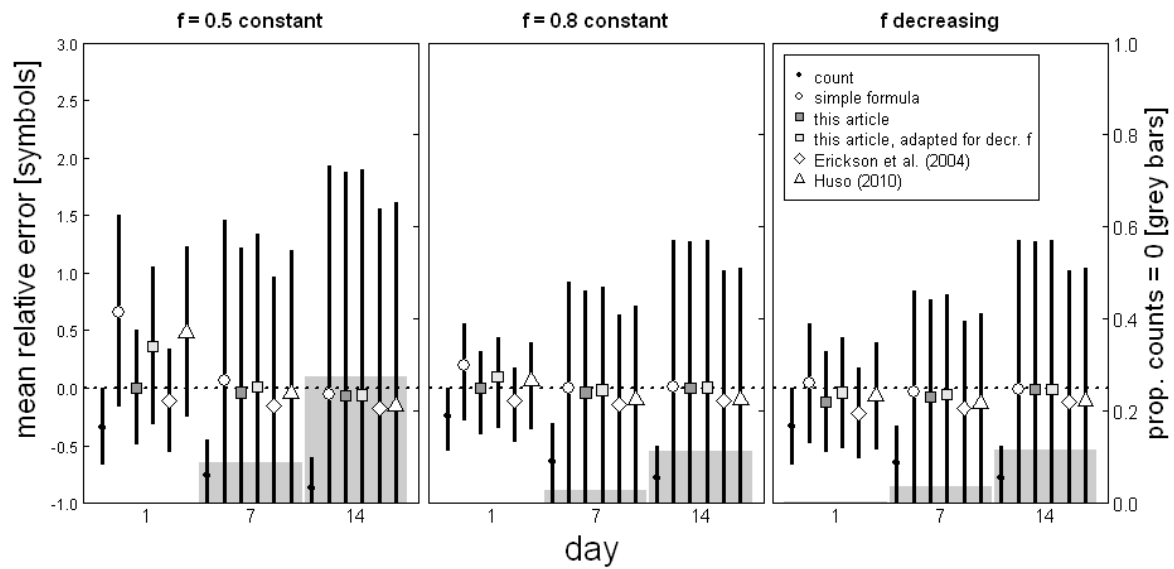
- 1 distribution of the fatalities or the uncertainty in the estimated searcher efficiency and
- 2 persistence probability (both were assumed to be known in our simulations).
- 3

1 Fig. 1



2  
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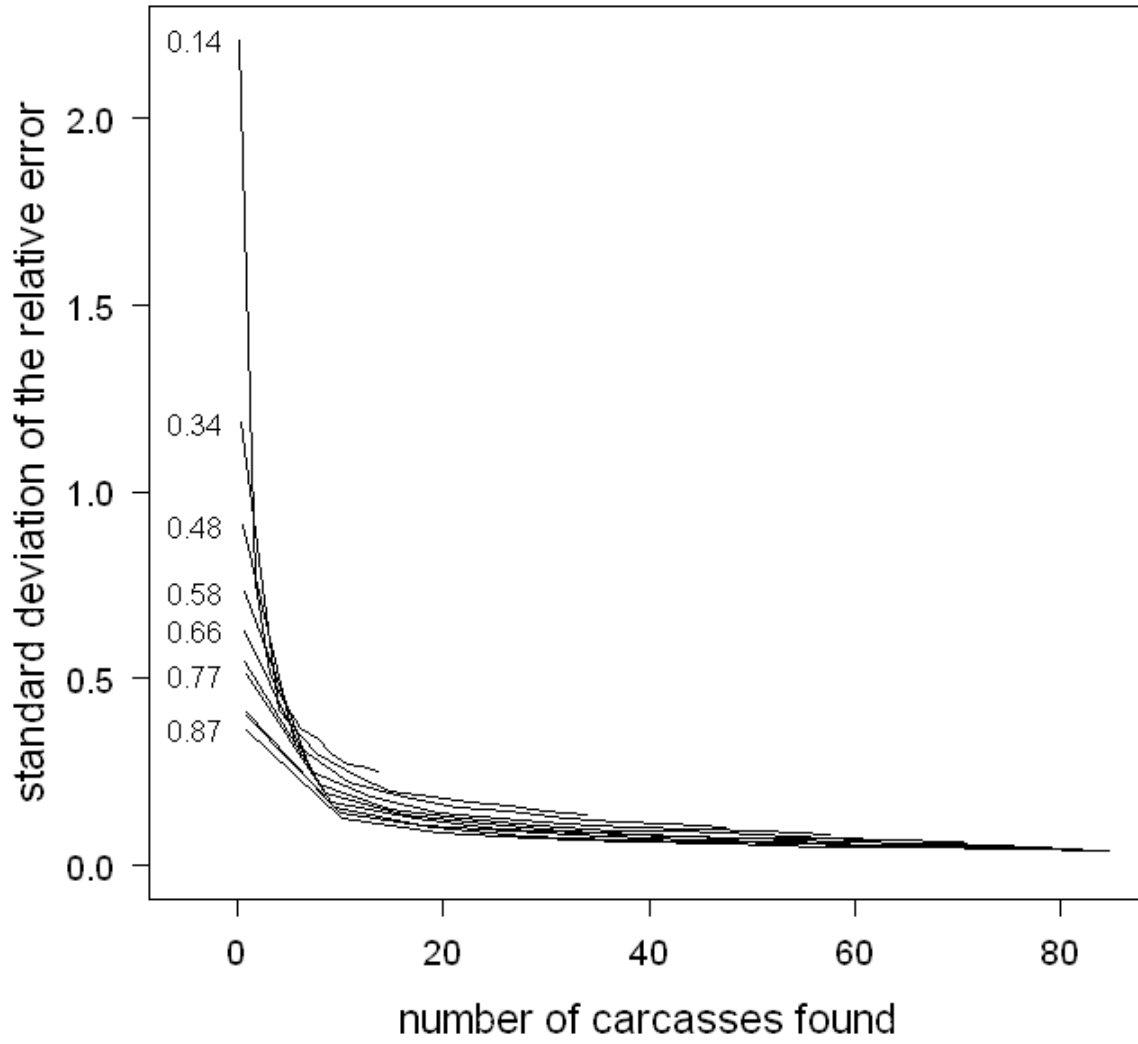
Fig. 2



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8  
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10

1

2 Fig. 3



3

1

2 **Appendix 1**3 **Derivation of the new formula to estimate carcass detection probability**

4 The table below contains the expected number of killed bats or birds that are present below a  
5 wind turbine for each day (1 to  $I$ ) of the study period, if an average of  $\bar{m}$  animals are killed  
6 per day. For each search the expected number of carcasses found is given in the last column.

7 The last row gives the sum of the expected number of animals killed and the sum of the  
8 carcasses found during all searches.

Search	Night/day	Expected number of killed bats present	Expected number of killed bats found
	1	$\bar{m} s$	
	2	$\bar{m} (s + s^2)$	
	...		
1. Search	$d$	$\bar{m} (s + s^2 + \dots + s^d) = \bar{m} s \frac{1 - s^d}{1 - s} = \bar{m} A$	$\bar{m} Af$
		with $A = s \frac{1 - s^d}{1 - s}$	
	$d + 1$	$\bar{m} (A(1-f)s + s)$	
	$d + 2$	$\bar{m} (A(1-f)s^2 + s + s^2)$	
	...		
2. Search	$2d$	$\bar{m} (A(1-f)s^d + s + s^2 + \dots + s^d) =$ $\bar{m} (A(1-f)s^d + A) = \bar{m} A[(1-f)s^d + 1]$	$\bar{m} A[(1-f)s^d + 1]f$
	$2d + 1$	$\bar{m} (A[(1-f)s^d + 1](1-f)s + s)$	
	$2d + 2$	$\bar{m} (A[(1-f)s^d + 1](1-f)s^2 + s + s^2)$	
	...		
3. Search	$3d$	$\bar{m} (A[(1-f)s^d + 1](1-f)s^d + A) =$ $\bar{m} (A(x+1)x + A)$ $= \bar{m} A((x+1)x + 1)$ $= \bar{m} A(x^2 + x + 1)$	$\bar{m} A(x^2 + x + 1)f$
		with $x = (1-f)s^d$	
	$3d + 1$	$\bar{m} (A(x^2 + x + 1)(1-f)s + s)$	
	$3d + 2$	$\bar{m} (A(x^2 + x + 1)(1-f)s^2 + s + s^2)$	
	...		
4. Search	$4d$	$\bar{m} (A(x^2 + x + 1)(1-f)s^d + A) =$ $\bar{m} A(x^3 + x^2 + x + 1)$	$\bar{m} A(x^3 + x^2 + x + 1)f$
n. Search	$nd = I$	$\bar{m} A(x^{(n-1)} + x^{(n-2)} + \dots + x + 1)$	$\bar{m} A(x^{(n-1)} + x^{(n-2)} + \dots + x + 1)f$



---

Sum of n Searches	$I$ $\bar{m} A(1 + (1+x) + (1+x+x^2) + \dots + (1+x + \dots + x^{(n-1)}))$ $= \bar{m} A(n + (n-1)x + (n-2)x^2 + \dots + (n-n)x^n)$ $= \bar{m} A \sum_{i=0}^n (n-i)x^i$	$\bar{m} Af \sum_{i=0}^n (n-i)x^i$ , where $A =$ $s \frac{1-s^d}{1-s}$ and $x = (1-f)s^d$
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---

1

## 2 **Appendix 2**

3 Here, we present a worked example using the statistical software R (R Development core  
 4 team 2010) to obtain a fatality estimate based on an empirical carcass count. It assumes that  
 5 both searcher efficiency and removal probability are experimentally assessed. By providing  
 6 this example, we show one possible way to obtain an estimate together with an uncertainty  
 7 measure (here a 95 % credible interval).

8 To obtain an uncertainty measure for the estimated number of fatalities, the following sources  
 9 of uncertainties have to be combined: 1) the randomness of the count process (e.g. two  
 10 searches will result in different numbers of carcasses found even if detection probability and  
 11 the true number of carcasses are the same), 2) the uncertainty in the estimate for removal  
 12 probability, 3) the uncertainty in the estimate for searcher efficiency. The uncertainty of the  
 13 fatality estimate which is due to the randomness of the count process is calculated with the  
 14 help of Bayes' theorem. This gives a posterior distribution of the number of fatalities based on  
 15 the carcasses counted and the (known) probability of detecting a carcass. To include the  
 16 uncertainty in the detection probability (that is based on the estimated searcher efficiency and  
 17 the estimated carcass removal probability) into this posterior distribution, we apply a Monte  
 18 Carlo simulation.

19 Note that the credible interval presented here shows the uncertainty in the fatality estimate for  
 20 the actual sample (the specific study period and study location) only, and it is only reliable for  
 21 short search intervals. This is because it does not take the temporal or spatial distribution of  
 22 the fatalities into account. If the aim of the study is to predict fatality in future or for different  
 23 turbines or if search intervals are large a model of the collision process (and presumably  
 24 additional data providing information about the temporal and spatial distribution of the  
 25 animal) is needed in addition to the search process model presented here to obtain a reliable  
 26 uncertainty measure (see Korner-Nievergelt et al. 2011 for an example).

27

### 28 **Example study description:**

29 Carcass searches were performed every second day during a 200 days study period (100  
 30 searches). For simplicity, we assume that 100 % of the area beneath a wind turbine is

1 searched. If only a part of the area is searched the probability that a killed animal falls into the  
 2 searched area ( $a$ ) has to be estimated (see Niermann et al. 2011). Then, the probability that a  
 3 killed animal is detected by a researcher is  $p^* = p^*a$ , and the uncertainty in the estimate of  $a$   
 4 can be included in the uncertainty measure for  $p^*$  by Monte Carlo methods in the same way as  
 5 shown here for the uncertainties in the estimates for searcher efficiency and carcass  
 6 persistence probability.

7  
 8 **Example data:**

9 **Number of carcasses found**  $C = 12$ , **searcher efficiency**  $f = 0.72$  (95 % CI: 0.62 – 0.81 from  
 10 experiments), i.e. the probability that a carcass that is lying on the ground at the time of the  
 11 search is found by the searcher, **carcass persistence**  $s = 0.84$  (95 % CI: 0.64 – 0.94 from  
 12 experiments), i.e. the probability that a carcass is not removed during 24 h. As CI, credible or  
 13 confidence intervals can be used.

14  
 15 **Estimating the number of fatalities with a credible interval**

16 ***Step 1:***

17 Describe the uncertainty in the estimates for searcher efficiency and carcass persistence  
 18 probability by a beta-distribution, i.e. transform the 95 % CI into the shape parameters of the  
 19 beta-distributions.

```
20
21 f <- 0.72; f.lower <- 0.62; f.upper <- 0.81
22 s <- 0.84; s.lower <- 0.64; s.upper <- 0.94
23
24 #-----
25 # function to transform the 95% CI into shape parameters of a beta
26 # distribution
27 shapeparameter<-function(m, lwr, upr){
28 # m = estimate
29 # lwr, upr = lower and upper limit of the 95 % credible or confidence
30 # interval
31 #-----
32 ci <- upr - lwr
33 sigma2 <- (ci/4)^2
34 a <- m*(m*(1-m)/sigma2-1)
35 b <- (1-m)*(m*(1-m)/sigma2-1)
36 list(a=a,b=b)
37 }
38 # end of function shapeparameter-----
```

```

1
2 f.a <- shapeparameter(f, f.lower, f.upper)$a
3 f.b <- shapeparameter(f, f.lower, f.upper)$b
4 s.a <- shapeparameter(s, s.lower, s.upper)$a
5 s.b <- shapeparameter(s, s.lower, s.upper)$b
6
7 Step 2
8 Define the parameters of the simulations and prepare the vector for the resulting posterior
9 distribution of the number of fatalities. Define a function to obtain the detection probability
10 from searcher efficiency, persistence probability and search interval. Here, we use the new
11 formula presented in this article. Define a function to obtain the posterior distribution of the
12 number of fatalities based on the number of observed carcasses and the detection probability.
13 This formula is based on the theorem of Bayes. Start the loop over step 3 and step 4.
14
15 maxn <- 500 # define a maximum for the number of fatalities
16 nsim <- 1000 # number of Monte Carlo simulations
17 # prepare a vector for the posterior density distribution
18 # of the estimated number of fatalities:
19 Npostdist <- numeric(maxn+1)
20
21 #-----
22 # function to obtain the probability of detecting a carcass
23 # given the searcher efficiency (f), persistence probability
24 # (s), search interval (d) and the total number of searches
25 # (n).
26 pcarcass <- function(s, f, d, n){
27 # s = probability that a carcass remains 24 hours
28 # f = probability that a carcass is detected by a
29 # searcher during a search given it persisted to the search
30 # d = (average) number of days between two searches
31 # n = number of searches (n * d = length of study period)
32 #-----
33 x <- (1-f)*s^d
34 A <- s*(1-s^d)/(1-s)
35 summep <- numeric(n)
36 for(k in 0:(n-1)) summep[k+1] <- (n-k)*x^k
37 p <- A*f*sum(summep)/(d*n)
38 p
39 }

```

```

1 # end of function pcarcass-----
2
3
4 #-----
5 # function to obtain the posterior density distribution of the
6 # number of fatalities based on a (known) probability that a
7 # carcass is detected (p) and the number of observed carcasses (nf)
8 posterior.N <- function(p, nf=0, maxN=50, ci.int=0.95, plot=TRUE,
9 dist=FALSE){
10 # p = probability that a killed animal is detected by a seacher
11 # nf = number of carcasses found
12 # maxN = maximal possible number of fatalities
13 # ci.int = size of the credible interval that should be calculated
14 # plot: posterior distribution is plotted if TRUE
15 # dist: posterior distribution is given if TRUE
16 #-----
17 N <- nf:maxN
18 if(nf==0) pN <- p*(1-p)^(N-nf)
19 if(nf>0) {
20   denom <- sum(choose(N, nf) * (1-p)^(N-nf))
21   pN <- choose(N, nf)*(1-p)^(N-nf)/denom
22   pN <- c(rep(0, nf), pN)
23   N <- c(rep(0, nf), N)
24 }
25
26 if(plot) plot(N, pN, type="h", lwd=5, lend="butt", xlab="Number of
27 fatalities", ylab="Posterior density")
28 index <- cumsum(pN)<ci.int
29 indexLower <- cumsum(pN)<(1-ci.int)/2
30 indexUpper <- cumsum(pN)<1-(1-ci.int)/2
31 if(nf==0) interval <- c(nf, min(N[!index]))
32 if(nf>0) interval <- c(min(N[!indexLower]), min(N[!indexUpper]))
33 if(interval[2]==Inf) cat("Upper limit of CI larger than maxN! -> increase
34 maxN\n")
35 expected <- min(N[!cumsum(pN)<0.5])
36 results <- list(interval=interval, expected=expected)
37 if(dist==TRUE) results <- list(interval=interval, expected=expected, pN=pN)
38 results
39 }
40 # end of function posterior.N-----
41
42 for(i in 1:nsim){

```

```

1
2 Step 3
3 Draw a searcher efficiency  $f$  at random from the beta distribution defined by f.a and f.b.
4 fr <- rbeta(1, f.a, f.b)
5
6 Draw a persistence probability  $s$  at random from the beta distribution defined by s.a and s.b.
7 sr <- rbeta(1, s.a, s.b)
8
9 Calculate the detection probability given sr, fr, search interval  $d=2$  and number of searches
10  $n=100$ .
11 pr <- pcarcass(sr, fr, d=2, n=100)
12
13 Step 4
14 Compute the posterior density distribution of the number of fatalities based on pr and the
15 observed number of carcasses (number found =12) using the function posterior.N.
16
17 postNtemp <- posterior.N(nf=12, p=pr, maxN=maxn, plot=FALSE, dist=TRUE)
18
19 Sum the posterior densities over all nsim simulations.
20
21 Npostdist <- Npostdist + postNtemp$pN
22 } # close loop i
23
24 Step 5
25 Scale the summed posterior distribution and extract median and 95 % credible interval.
26
27 Npostdist.sc <- Npostdist/nsim
28 indexLower <- cumsum(Npostdist.sc) < 0.025
29 indexMedian <- cumsum(Npostdist.sc) < 0.5
30 indexUpper <- cumsum(Npostdist.sc) < 0.975
31 lower <- min(c(0:maxn)[!indexLower])
32 estimate <- min(c(0:maxn)[!indexMedian])
33 upper <- min(c(0:maxn)[!indexUpper])
34 lower; estimate; upper
35
36 As a result we receive an estimate of 17 fatalities with a 95 % credible interval of 12-31
37 fatalities.

```

1 The posterior distribution of the number of fatalities is plotted:

2

```
3 plot(0:maxn, Npostdist.sc , type="h", lwd=5, lend="butt", xlab="Number of  
4 fatalities", ylab="Posterior density", xlim=c(0,50))
```

5

6

## 7 **Electronic supplement 1**

8 **Fig.** Effect of assuming a constant removal probability when it is actually decreasing or

9 increasing in time: Proportion of remaining carcasses (solid black lines) and the

10 corresponding daily removal probabilities (dotted black lines) for four simulation scenarios.

11 To obtain the proportions of remaining carcasses and the removal probabilities Weibull

12 distributions for the persistence times were assumed. For simulating decreasing removal

13 probabilities with time,  $\alpha$  was set to 0.7, and for increasing removal probabilities  $\alpha$  was set to

14 1.3.  $\lambda$  was then obtained using the mean assumed persistence time  $T$ :  $\lambda = \frac{\Gamma\left(1 + \frac{1}{\alpha}\right)}{T}$ . The

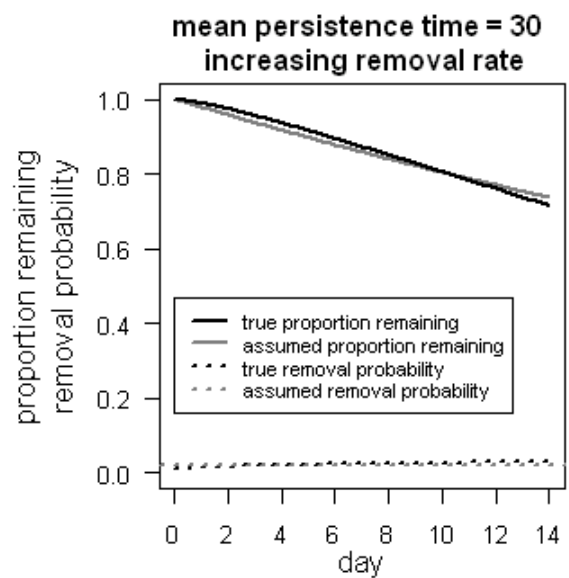
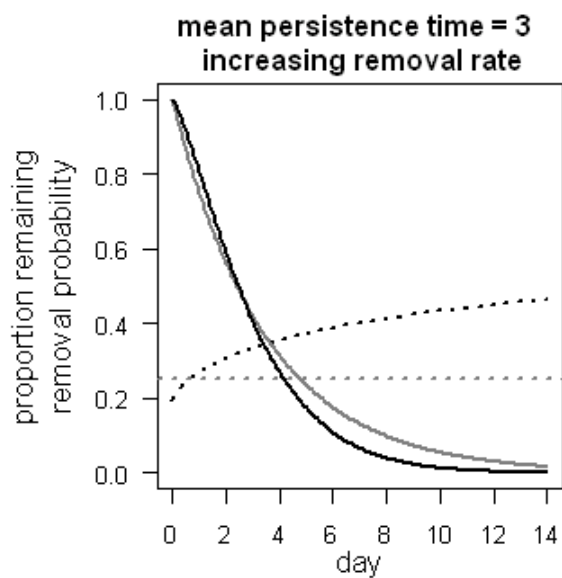
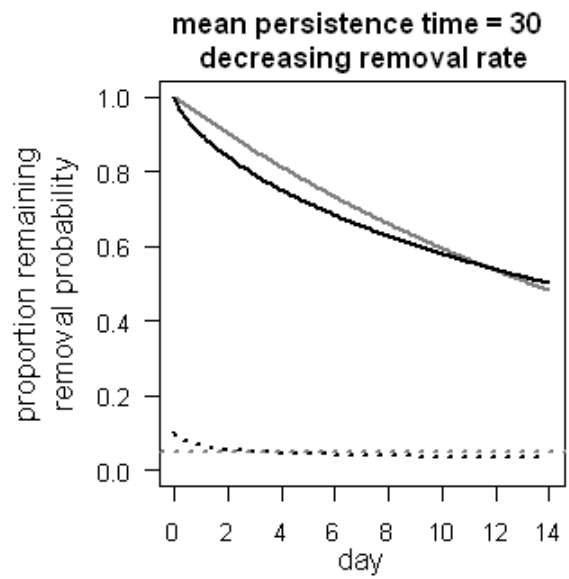
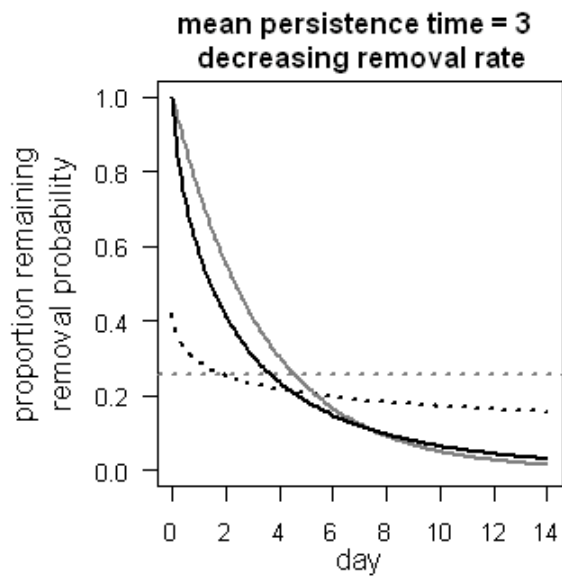
15 proportion of remaining carcasses per day is  $S(t) = e^{[-(\lambda t)^\alpha]}$ , and the daily removal probability

16  $(1 - s(t)) = 1 - \frac{e^{[-(\lambda(t+1))^\alpha]}}{e^{[-(\lambda t)^\alpha]}}$ , where  $s$  is the probability that a carcass remains ("survives") one

17 day. Grey solid lines are the proportion of remaining carcasses under the (false) assumption of

18 a constant removal rate (grey dotted lines).

19

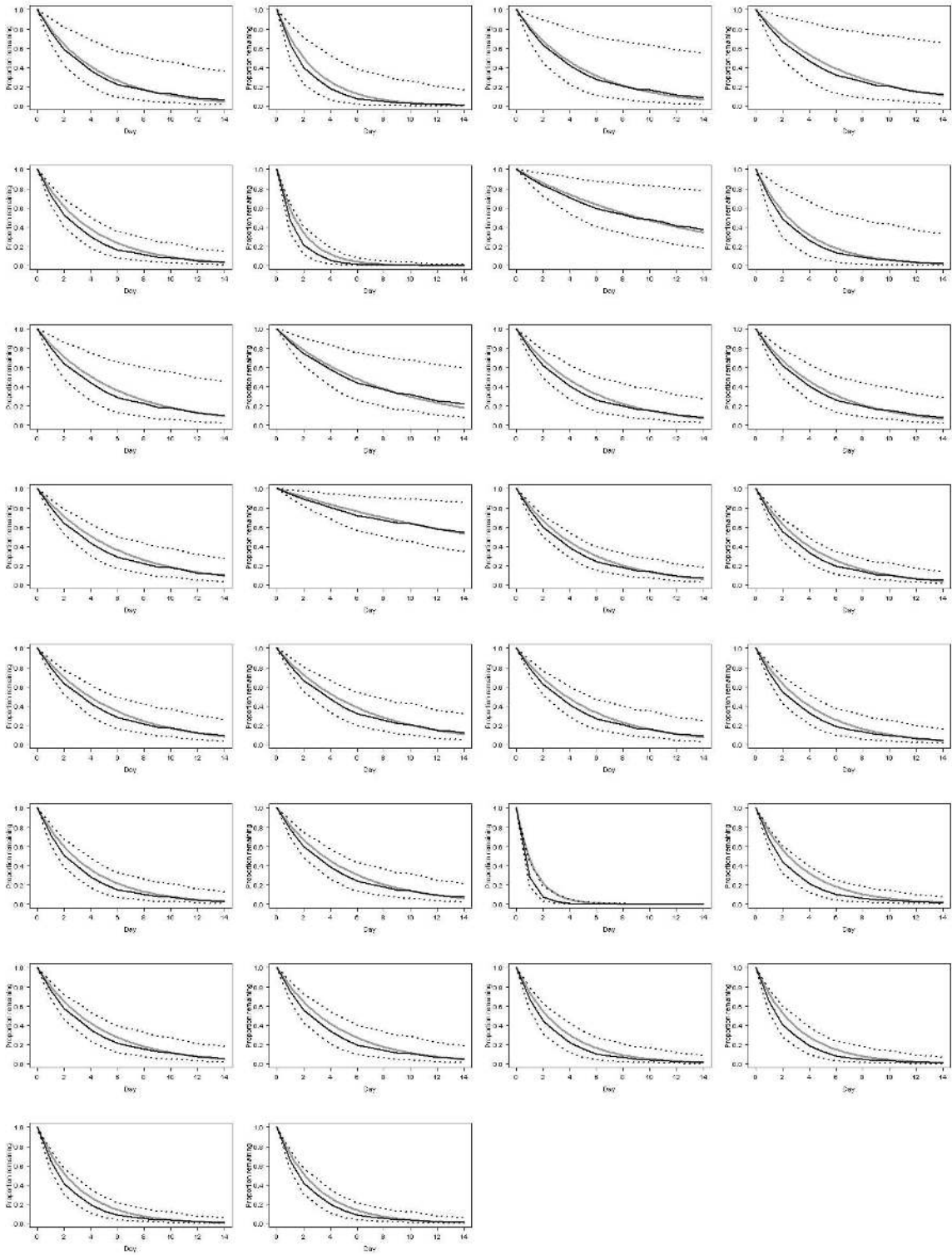


- 1
- 2
- 3
- 4

## 1 **Electronic supplement 2**

2 **Fig.** Proportion of remaining carcasses (bats, brown mice) at 30 wind energy turbines in  
3 Germany (see Niermann et al. 2011) over the first 14 days. The black line gives the  
4 proportion of remaining carcasses (with 95 % confidence interval within the dotted lines)  
5 estimated by a non-parametric Cox proportional hazard model with turbine as a grouping  
6 factor. This model does not assume constant removal rates. The grey line gives the same  
7 proportion estimated by assuming an exponential distribution of the persistence times, i.e.  
8 constant removal rates. In total 662 carcasses (7 – 35 per turbine, 32 bats and 630 brown  
9 mice) were used.





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4