A method for inferring extinction based on sighting records that change in frequency over time

Jari•[1]*, I. and Ebenhard[2], T.

[1] Institute for Multidisciplinary Research, Kneza Viseslava 1, 11000 Belgrade, Serbia; Phone: +381 11 2078 477; Fax: +381 11 3055 289; E-mail: ijaric@imsi.rs

[2] Swedish Biodiversity Centre (CBM), Swedish University of Agricultural Sciences, Box 7007, S-750 07 Uppsala, Sweden; Phone: +46 18 672 268; Fax: +46 18 673 537; E-mail: torbjorn.ebenhard@cbm.slu.se

*Corresponding author; Mailing address: Institute for Multidisciplinary Research, Kneza Viseslava 1, 11000 Belgrade, Serbia; E-mail: ijaric@imsi.rs

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Abstract

It is a very important but also a very difficult task to establish for how long a certain species has to remain unregistered before we can declare it extinct. The wrong assumption regarding species extinction could result in a type I or type II statistical error, leading to inappropriate management actions or even species extinction. Recent development of the methods for inferring the threat of extinction, when the only available information is a record of sightings, has enabled a quantitative approach to the problem. In this study the authors present an index that infers extinction probability based on trends in sighting intervals. The study comprises a description of the sighting trend index, a sensitivity analysis, as well as an application of the index to the sighting record of the Black-footed ferret (*Mustela nigripes*). The main advantage of this method could be its sensitivity to changes in sighting frequency within the sighting record. However, further testing of the method on different data sets could be important for gaining additional knowledge regarding its adequate application in the field of conservation biology.

1. Introduction

How long must a certain species remain unrecorded before we can declare it extinct? Classification of a species as extinct is a very difficult task and often surrounded with uncertainty (Burgman et al. 1995, McInerny et al. 2006). There have been many cases where a species was declared extinct and later rediscovered (Regan et al. 2000, Roberts & Kitchener 2006), because species that become increasingly rare before their final extinction may continue to exist unseen for many years (Roberts & Solow 2003). If the assumption regarding the species extinction is wrong, it will result either in a type I or type II statistical error. Following a false assumption that the species is extinct, inappropriate management actions, or the lack of them, may lead to the actual species extinction. The alternative situation may lead to costly and unnecessary sampling activities (Grogan & Boreman 1998).

According to IUCN (2001), a taxon is presumed extinct when exhaustive surveys in known and/or expected habitat, at appropriate times (diurnal, seasonal, annual), and throughout its historic range have failed to record an individual. However, this "rule of thumb" approach has too often been used to assess conservation status of a species, and more formal methods, preferably quantitative, could help to ensure that status assessments are scientifically defensible and that resources are efficiently allocated to the conservation programs (McCarthy 1998).

One way of addressing the discussed concern has been given by a recent development of quantitative methods for inferring probability of extinction when the only available information is the record of sightings. The idea of using sighting records to infer the extinction probability and the time of extinction was first introduced by paleobiologists (Strauss & Sadler 1989, Marshall 1990). Within the field of conservation biology and the current species extinctions, this approach was applied for the first time by Solow (Solow 1993*a*), who provided an equation for inferring extinction of a species based on sightings over a series of time units. As shown in Figure 1, sightings within the observation period are arranged from the first to the last, and the time of the last sighting marked with the t_n.

Solow's equation expresses the probability of presence (species survival) in relation to the number of time units in which the species was recorded (n) within the period, given that the sightings are equally likely to occur during the whole observation period (T):

$$p = \left(\frac{t_n}{T}\right)^n \qquad (\#1)$$

This equation, together with a special model for declining populations (Solow 1993*b*), were soon followed by development of other methods. Overall, five methods that provide the probability of extinction have been consecutively developed, and we will briefly describe them within the following section.

Burgman et al. (1995) developed a similar equation to the above presented one, which, instead of a number of time units with sightings, used the total number of observed individuals. Since population decline is often characterized by longer and longer periods during which the species is not observed, Burgman et al. (1995) also introduced a so-called "runs test": a method that calculates the probability that the species will be recorded again during a period that is either as long as or longer than the longest observed run of absence. Solow and Roberts developed a non-parametric equation (Equation #2, Solow & Roberts 2003) that does not require a complete series of sighting records, and which can therefore be advantageous when only a few records are available. They have also introduced a model that tests extinction by an estimate of the shape parameter of the Weibull extreme value distribution (Roberts & Solow 2003, Solow 2005). Finally, McInerny et al. (2006) developed a sighting rate model, which yields the probability that another sighting will occur, based on the previous sighting rate which is unbiased by different length of periods of observation. The basic idea underlying all these methods is that the confidence in the continued existence of a species is greater when it has been more recently sighted (Roberts & Solow 2003). Specifically, they take into account the following two key parameters: the number of time units with the recorded sightings (n) and the time elapsed since the last sighting ($T - t_n$). Recent evaluations of the performance and reliability of these methods were conducted by Rivadeneira et al. (2009) and Vogel et al. (2009).

Until recently, IUCN and CITES have arbitrarily decided on 50 years without sightings as the threshold value to declare a species as extinct (Reed 1996). However, the period that we are prepared to wait before we conclude that a species has become extinct should be based on the frequency with which it was seen before the last observation (Burgman et al. 1995). As stated by Solow (2005), a threshold value that implies extinction should be related to previous sighting rates, and for species with a high sighting rate, a relatively short period without sightings would indicate extinction, and *vice versa*. Since previous authors did not consider the trend of the sighting intervals' length in equations that have been developed so far, there is a present need to introduce a method that would be sensitive to this aspect of the sighting record.

In this paper we present a new index that infers probability of extinction based on the average length and trends in the sighting intervals. The sighting trend index will be described together with a sensitivity analysis and thereafter applied to the sighting record of the Black-footed ferret (*Mustela nigripes*).

2. Sighting trend index

Solow/Roberts non-parametric equation (Solow & Roberts 2003) was used as a basis for the development of the index:

$$p = \left(\frac{t_n - t_{n-1}}{T - t_{n-1}}\right) \qquad (\#2)$$

This equation gives the probability of extinction using the time of the last sighting (t_n), the time of the second most recent sighting (t_{n-1}) and the end of the observation period (T). To incorporate the average frequency of sightings within the equation, we have replaced the time between the last two sightings (t_n - t_{n-1}) with the average time elapsed between each two sightings.

If time is considered as discrete and the sighting records are arranged as a series of time units (t) with sightings within the observation period (with the first time unit labelled 1 and the last T) ordered from the earliest to the latest, $t_1 < t_2 < . . . < t_n$ (Figure 1), then the average time elapsed between each two sightings can be calculated as:

$$I = \frac{\sum_{x=2}^{n}(t_x - t_{x-1})}{n-1} = \frac{t_n - 1}{n-1} \qquad (\#3)$$

The denominator in Equation #2 (T - t_{n-1}) can be rewritten as [(T - t_n) + (t_n - t_{n-1})]. Therefore, if the time between the last two sightings (t_n - t_{n-1}) in Equation #2 is replaced with the average time elapsed between each two sightings [(t_n - 1) / (n – 1)], the probability that the species is still present would then be:

$$p = \frac{\frac{t_n - 1}{n - 1}}{\frac{t_n - 1}{n - 1} + (T - t_n)} \qquad (\#4)$$

Here, n is the number of time units with sightings, and (T - t_n) represents the period since the last sighting; (t_n - 1)/(n - 1) represents the average length of the intervals between sightings. Multiple sightings within the same time unit are treated as a single sighting. The last time unit (T) corresponds to the final year of the time series.

In case of a species whose rate of sighting has been changing over time (i.e., either increasing or decreasing), the equation can be modified to reflect this change. If the period between two sightings is expected to be longer than between the previous two, a longer time after the last sighting should be needed to infer extinction, and *vice versa*. Therefore, a coefficient of trend in sighting intervals (c) can be included in the formula, which represents the average change in length of intervals between each two consecutive sightings:

$$c = \frac{\sum_{x=2}^{n-1} \left[(t_{x+1} - t_x) - (t_x - t_{x-1}) \right]}{n - 2} \qquad (\#5)$$

Note that if the frequency (i.e., the inverse time interval) decreases, the coefficient is positive, otherwise it is negative. The probability would then be:

$$p = \frac{\frac{t_n - 1}{n - 1} + c}{\frac{t_n - 1}{n - 1} + c + \left(T - t_n\right)} \qquad (\#6)$$

The coefficient of trend in sighting intervals (*c*) was included in both the numerator and denominator of the Equation #6 to allow the resulting probability to range between the two extreme values (i.e., 0 and 1). For instance, in case the last sighting occurred in the present year, (T - t_n) would reach the value of 0 and consequently probability would assume the value 1.

There are two very important underlying assumptions that must be fulfilled, for the index to provide reliable results. One is that all observations of a species have to be both incidental and independent of each other (Solow 1993, Burgman et al. 1995). The second assumption is that the sighting effort does not change over time. According to Solow & Roberts (2003), variation in sighting effort is an important potential source of variation in the sighting rate, but the assumptions may be reasonably met if sightings arise from accidental encounters. Most authors employ a 0.05 probability as the threshold value, below which the species can be considered as extinct (Solow & Roberts 2003, McInerny et al. 2006, Roberts & Kitchener 2006, Carpaneto et al. 2007).

2.1. Sensitivity analysis

The sighting interval index (Equation #4) is sensitive to two variables, the number of time intervals in the time series since the last observation ($T - t_n$), and the average length of sighting intervals $(t_n - 1)/(n - 1)$. The Equation #6 is also sensitive to the trend of sighting intervals (c). Sensitivity of probability of extinction to these factors was examined, and the results are presented in Table 1. As shown, the index produces values that indicate that the population does not exist anymore ($p<0.05$) when the period since the last sighting exceeds 20 times the average sighting interval (together with the trend of sighting intervals in Equation #6). The previous IUCN threshold of 50 years without sightings (Reed 1996) would then correspond to species whose average sighting interval was less than 2.5 years or, according to Equation #6, for species whose average sighting interval was initially larger but steadily decreasing in time.

It is important to note that, although the presented index is sensitive to the average length and trend in sighting intervals, it is much less sensitive to the number of observations (n). The ability of the index to be unaffected by the total length of the sighting period is similar to the sighting rate model developed by McInerny et al. (2006). This could be advantageous because of inequalities that may arise between records of different species in both the number of sightings and in the length of the entire observation period. That could obstruct comparability of sighting records among species, as well as the applicability of methods that are sensitive to these features (McInerny et al. 2006).

The parameter capturing trends in sighting intervals (c) in Equation #6 provides sensitivity of the method to different patterns of the sighting record. For species whose sighting frequency has been decreasing (i.e., a gradually longer periods between sightings are recorded), *c* would reach a positive value. Equation #6 would, therefore, require a longer period since the last sighting to reach a level of significance ($p<0.05$), and *vice versa*. This is in accordance with the real situation, since the next sighting in a decreasing population should appear after the longer period than between the last two sightings, and the probability of extinction should thus be lower even if the species was not recorded for several years. In other words, the model would return a higher value for a species with decreasing sighting frequency, than for a species with stable sighting frequency, if the time since the most recent sighting is the same for both species. However, it should be taken in consideration that this index is not sensitive to the distribution of the change in the trend, since it can not distinguish between changes in length of the sighting interval that appeared at the beginning or at the end of the observation period.

To test the performance of the presented index under different extinction and sampling scenarios, as well as to compare its behaviour and reliability with the other models and indices, we have applied approach presented by Rivadeneira et al. (2009). Artificial sighting record datasets were generated and simulated in an Excel spreadsheet using the PopTools module (Hood 2005). Confidence intervals that were produced by Equations #4 and #6 were evaluated based on their statistical coverage (i.e., on the appropriateness of the 95% confidence intervals). As proposed by Rivadeneira et al. (2009), an accurate and precise method would have 95% of simulated extinctions falling within the upper bound (95%) of the confidence interval.

Equations #4 and #6 were modified to produce the upper bound of the 1- • confidence intervals (• =0.05). This was done by inverting both equations, so they estimate *T* at threshold probability value (*p*=0.05):

$$T_{ci} = t_n + \frac{t_n - 1}{n - 1} \times \frac{1 - \alpha}{\alpha} \quad (\#7)$$

$$T_{ci} = t_n + \left(\frac{t_n - 1}{n - 1} + c \right) \times \frac{1 - \alpha}{\alpha} \quad (\#8)$$

where Equations #7 and #8 represent, respectively, upper bounds (95%) of the confidence interval of Equations #4 and #6.

In order to enable easier comparison with the evaluation that was conducted by Rivadeneira et al. (2009) on other methods, the same values of simulation parameters were applied. Scenarios were developed with two different probabilities of occurrence: a high (P_o=0.8) and low one (P_o=0.2), two different scenarios of extinction (sudden vs. gradual), three different probabilities of sampling (P_s: uniform, decreasing and increasing, used as a measure of sighting effort), and three different lengths of sighting time series (20, 60 and 120 years). In total, different combinations of these parameters derived 36 different scenarios. Each scenario was simulated with 20 000 iterations, and the result was expressed as a percent of simulations that had the actual extinction event falling within the estimated 95% confidence interval. The method that produces narrow confidence intervals will have coverage below the nominal percentage (95%) and thus be prone to Type I error, and *vice versa*, the method with systematically broad confidence intervals (coverage above 95%) will be too conservative and therefore more prone to Type II error (Rivadeneira et al. 2009). For more information on scenario development and simulation, see Rivadeneira et al. (2009).

Results of all simulations are presented in Figures 2 and 3. When compared with the other existing methods (see Rivadeneira et al. 2009), it is apparent that the performance of both equations resembles more those methods that were developed by Solow & Roberts (2003) and Roberts & Solow (2003). Confidence interval coverage of these two methods has been also more frequently positioned above than below the threshold value (>95%). This similarity in behaviour is probably not surprising, since the method presented here was derived from Solow/Roberts non-parametric equation (Solow & Roberts 2003). As stated by Rivadeneira et al. (2009), this group of methods generally outperforms the methods developed by Strauss & Sadler (1989), Solow (1993*a*) and McInerny et al. (2006), since it produces more reliable results and could be also less likely to make a Type I error. On the other hand, these methods tend to be much more conservative and prone to Type II error.

The Equation #6 has generally produced coverage that was closer to 95% threshold than the coverage of Equation #4, meaning that the inclusion of coefficient *c* in the equation increased the precision of the method. Both equations have produced estimations that were more precise under gradual extinction than under the instant extinction, and were also more precise under low sighting probability than under high sighting probability (Figure 2). Furthermore, shorter sighting records had an increased variation among results of different scenarios, especially in performance of Equation #6 (Figure 3). In such short sighting records (i.e., 20 years), Equation #4 was less prone to Type I error than Equation #6 (Figure 3). Confidence intervals were always more conservative under uniform sampling than under either increasing or decreasing sampling effort.

3. Example

As an illustration of the method application, the sighting records of the Black-footed ferret in the State of Wyoming for the period January 1972 – December 1990 were used (Table 2, Solow 1993*b*). This data set was also used by Solow (1993*b*) to illustrate his method for declining populations. Although the Black-footed ferret was preserved in captivity and later successfully reintroduced back into the wild (Dobson & Lyles 2000, Wisely et al. 2008), these records can still be useful as an example of the assessment of extinction in a declining population. In this example, months were used as time units. In order to enable easier comparability with the result of a model published by Solow (1993*b*), the same endpoint of the observation period was used (December 1990). The total length of the observation period (T) is 223 (with June 1972 as the first time unit), the number of observations (n) is 28, and ($T - t_n$) is 75 (October 1984 – December 1990). The average period between sightings is 5.444, and the c value is positive (0.038), indicating a small average decline in sighting frequency. Due to a small value of coefficient c, Equation #4 and #6 both provide the same resulting value of p=0.068.

The method applied by Solow (1993*b*) provided slightly lower value, p=0.050. Other methods (Solow 1993*a*, Burgman et al. 1995, Solow & Roberts 2003, McInerny et al. 2006) would produce values that range from 0.000 to 0.026. These models use other information within the same datasets, and the first sighting is often omitted in them, providing therefore T=222 and n=27.

In the case of the Black-footed ferret, the sighting trend index presented in this paper provides more conservative results and, due to a weak trend of decline in sighting records, the result remains unchanged even with the inclusion of a coefficient of trends in sighting intervals (c). This could be probably due to the fact that this index is mostly dependent on the overall sighting frequency, which was low throughout the observation period (on average, one sighting every 5.444 years). On the other hand, the resulting values were near the threshold level (p=0.05), and very similar to the one provided by the other method for declining populations (Solow 1993*b*). This indicates that at that time, prior to reintroduction events, the disappearance of Black-footed ferret was imminent. Equations #7 and #8 point out, respectively, to May and June 1993 as the upper bound (95%) of the confidence interval.

4. Discussion

The aim of this study was to present an alternative method for the assessment of the extinction probability, which is based on the sighting records that show trends in sighting intervals. Although more advanced assessment methods, such as Population Viability Analysis (PVA), could represent a more reliable approach to assess the extinction threat of a species (Akçakaya & Sjögren-Gulve 2000), sighting records represent in certain cases the only available data for the quantitative assessment. In such cases, these methods can represent the only available quantitative approach, which could provide validity and reliability to extinction assessments.

Solow (2005) stated that the discussed group of methods has a significant potential in paleobiology, through the assessment of mass extinction events by stratigraphic locations of fossil finds. One of the recently advocated potential applications of these methods is their use in evaluation of the invasive species eradication programs (Rout et al. 2009). Furthermore, as proposed by many authors (McCarthy 1998, Regan et al. 2000, McInerny et al. 2006, Robbirt et al. 2006), such indices may not only be used for estimating the probability of species extinction, but also to infer threat and decline in species that are considered to be still extant. As such, they should be included in the evaluation criteria for all IUCN categories (Robbirt et al. 2006).

Sensitivity analysis has shown that the presented method is more robust to varying scenarios when compared to methods of Solow (1993*a*) and McInerny et al. (2006), and less prone to Type I error (Rivadeneira et al. 2009). On the other hand, it is generally more conservative and more prone to Type II error. As stated by Rivadeneira et al. (2009), this can be advantageous if one wishes to be on safe side, since false inference of extinction could potentially be more harmful.

McCarthy (1998) and Robbirt et al. (2006) suggested that it could be prudent to use a number of complementary methods, since each can be sensitive to different characteristics of the collection/sighting records. According to McCarthy (1998), their combination should enhance the overall ability to detect extinction. We do not fully agree with this opinion, since such approach may result in confounding estimations. *A* *priori* analysis of characteristics of the species or population in question and its sighting record might indicate which method offers the best potential to produce reliable results.

The evaluation of the proposed method indicates that it performs best when applied to the sighting records of species that are believed to exhibit gradual extinction, as well as to those whose probability of sighting has been generally low. The inclusion of the coefficient of trend in sighting intervals (c) in the method could be beneficial, since it improves the precision of the method. On the other hand, it should not be used in a case of very short sighting records, where its inclusion may lead to an increased chance of falsely inferring extinction. Similar to all other methods, this method is unable to distinguish between the distribution of changes in trend within the observation period (e.g. whether the change in frequency has appeared at the beginning or at the end of the observation period). As a result, future research should be also focused towards development of the methods that could be able to overcome this problem.

To conclude, our study presented a sighting trend index, an assessment of its sensitivity and an illustration of its application. It could be of crucial importance, however, to conduct further testing of this method on different data sets, which could improve our knowledge regarding the model's potential and adequate application in the field of conservation biology. In the present situation of an ongoing mass extinction on a global scale, methods that are able to infer extinction will unfortunately become more and more important.

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Table 1. Probability (p) of extinction of a species (based on Equations #4 and #6), given different values of the average sighting interval and the total number of time intervals since the species was last observed (T - t_n). Significant probabilities (p<0.05) are shown in italics. Values in column headings represent average sighting intervals [(t_n - 1)/(n - 1)] if Equation #4 is applied, or average sighting intervals with sighting coefficient [(t_n - 1)/(n - 1) + c] if Equation #6 is applied.

T - t_n	Average sighting interval				
	1	2	3	4	5
1	0.50	0.67	0.75	0.80	0.83
2	0.33	0.50	0.60	0.67	0.71
3	0.25	0.40	0.50	0.57	0.63
4	0.20	0.33	0.43	0.50	0.56
5	0.17	0.29	0.38	0.44	0.50
6	0.14	0.25	0.33	0.40	0.45
7	0.13	0.22	0.30	0.36	0.42
8	0.11	0.20	0.27	0.33	0.38
9	0.10	0.18	0.25	0.31	0.36
10	0.09	0.17	0.23	0.29	0.33
20	0.05	0.09	0.13	0.17	0.20
30	*0.03*	0.06	0.09	0.12	0.14
40	*0.02*	0.05	0.07	0.09	0.11
50	*0.02*	*0.04*	0.06	0.07	0.09
60	*0.02*	*0.03*	0.05	0.06	0.08
70	*0.01*	*0.03*	*0.04*	0.05	0.07

80	*0.01*	*0.02*	*0.04*	0.05	0.06
90	*0.01*	*0.02*	*0.03*	*0.04*	0.05
100	*0.01*	*0.02*	*0.03*	*0.04*	*0.05*

Table 2. Sighting record of the Black-footed ferret in Wyoming for the period January 1972 – December 1990 (from Solow 1993*b*).

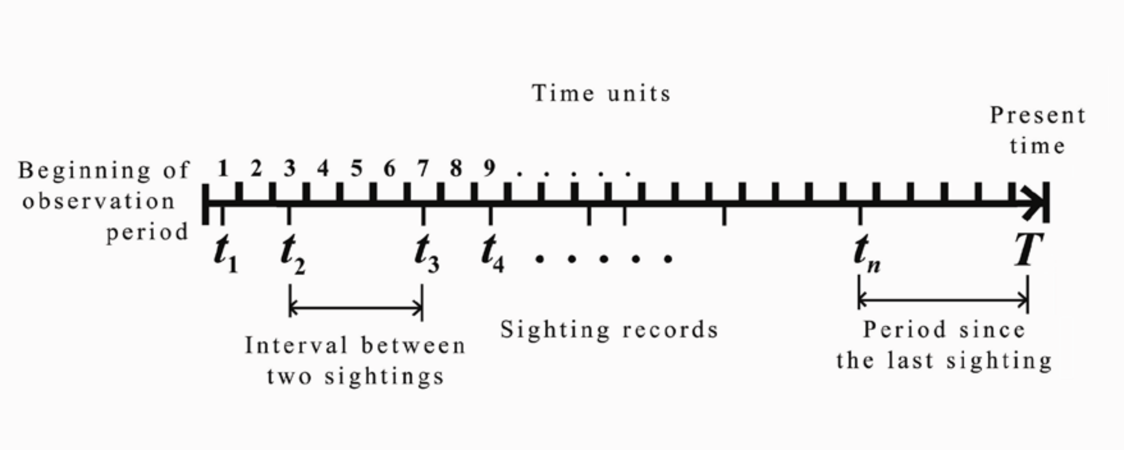
Year	Month					
1972	6	7	8	10		
1973	5	6	7	8	9	10
1974	6	7				
1975	5	8	10			
1976	5	9	10			
1977	6					
1978						
1979	6					
1980						
1981	9	10				
1982	2	3	7			
1983	7					
1984	7	9				

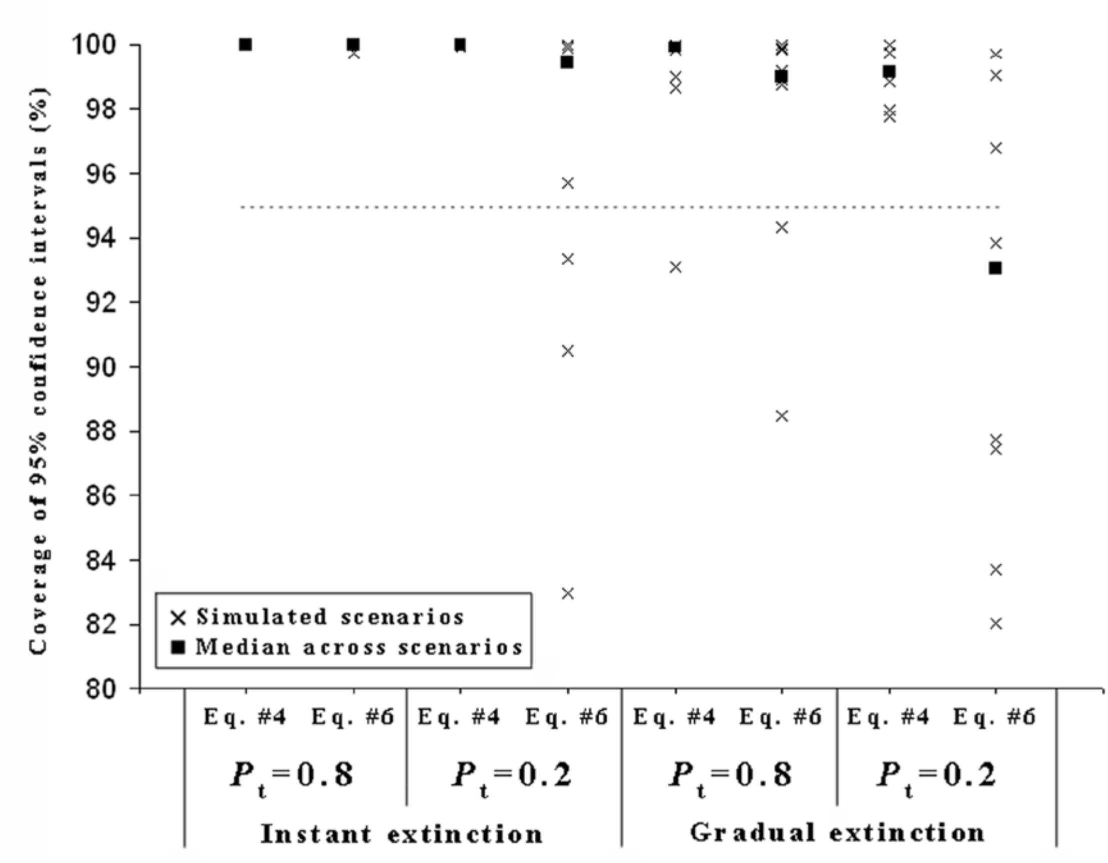
Figure caption:

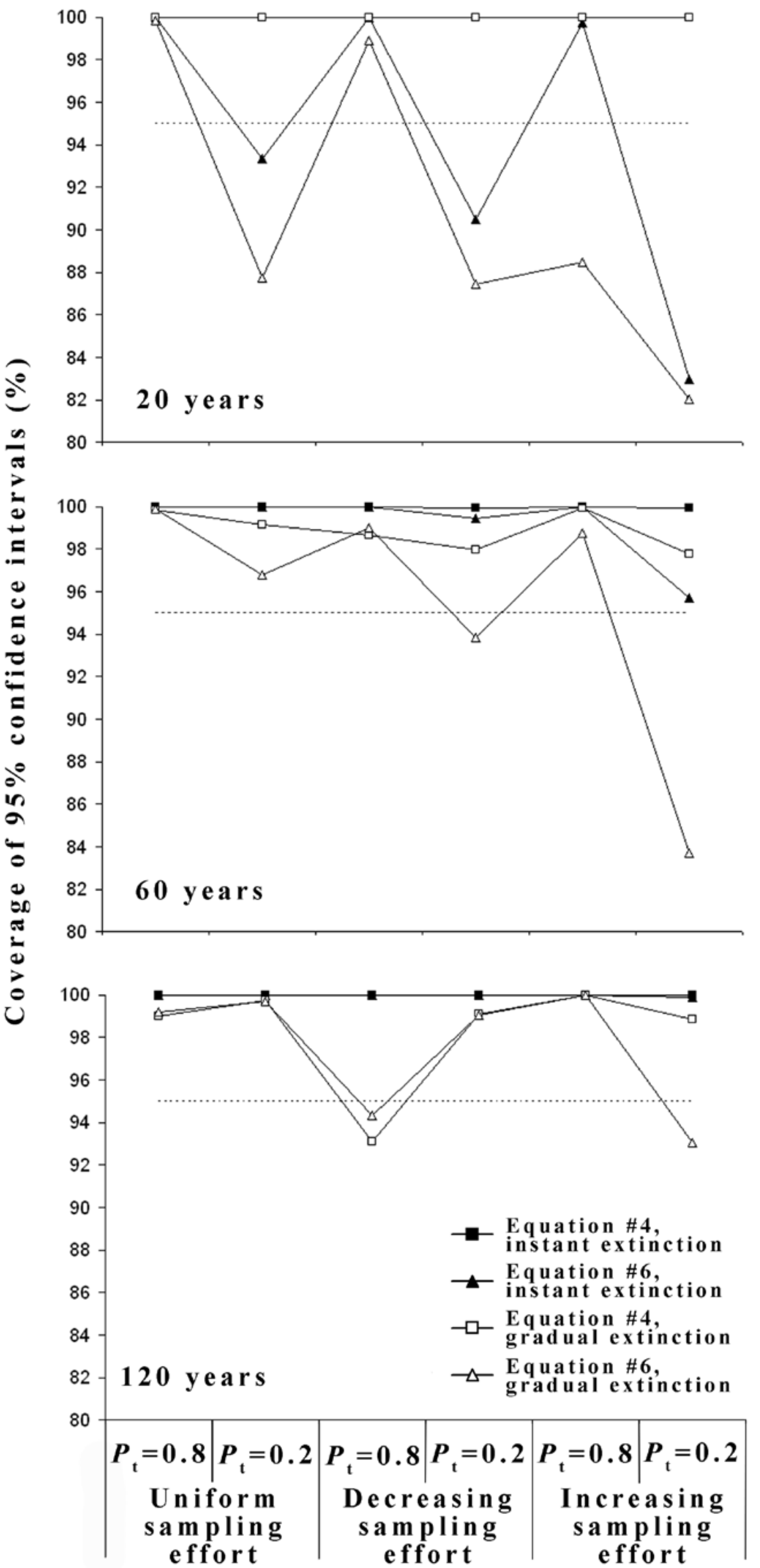
Figure 1. A schematic representation of the observation period. Upper side of the timeline represents time units (e.g. years), lower side represents sighting records (t_1, t_2, t_3, t_4,... t_n).

Figure 2. Median coverage of 95% confidence intervals of the upper bounds of extinction times for the two presented equations (Eq. 4 and Eq. 6), under different sighting probabilites (P_t) and different types of extinction, calculated across 36 different simulation scenarios (see Fig. 3). The broken line shows the threshold value (95%) indicating a perfect coverage (according to the approach by Rivadeneira et al. 2009).

Figure 3. Coverage for 95% confidence intervals of the upper bounds of extinction times, according to two presented equations (Eq. 4 and Eq. 6) under different simulation scenarios: different lengths of the sighting record (20, 60 and 120 years), sudden vs. gradual extinction, sighting probability (P_t) of 0.2 vs. 0.8, and different scenarios of sampling effort (uniform, decreasing or increasing). The broken line shows the threshold value (95%) indicating a perfect coverage (according to the approach by Rivadeneira et al. 2009).


Time units
Present time
Beginning of observation period
1 2 3 4 5 6 7 8 9 . . . . . .
t1 t2 t3 t4 . . . . . tn T
Interval between two sightings
Sighting records
Period since the last sighting


Coverage of 95% confidence intervals (%)
100
98
96
94
92
90
88
86
84
82
80
Simulated scenarios
Median across scenarios
Eq. #4
Eq. #6
Eq. #4
Eq. #6
Eq. #4
Eq. #6
Eq. #4
Eq. #6
P_t=0.8
P_t=0.2
P_t=0.8
P_t=0.2
Instant extinction
Gradual extinction



Coverage of 95% confidence intervals (%)
100
98
96
94
92
90
88
86
84
82
80
20 years
60 years
120 years
Equation #4, instant extinction
Equation #6, instant extinction
Equation #4, gradual extinction
Equation #6, gradual extinction
P_t=0.8
P_t=0.2
Uniform sampling effort
Decreasing sampling effort
Increasing sampling effort

1