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“I tawt I taw a puddy tat!": extinction and uncertain sightings of the Barbary lion

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As species become rare and approach extinction, purported sightings can be controversial, especially when scarce management resources are at stake. We report a Bayesian model where we consider the probability that each individual sighting is valid. Obtaining these probabilities clearly requires a strict framework to ensure that they are as representative as possible. We used a process, which has proven to provide accurate estimates from a group of experts, to obtain probabilities for the validation of 35 sightings of the Barbary lion. We considered the scenario where experts are simply asked whether a sighting was valid, as well as when we asked them to score the sighting based on distinguishablity, observer competence, and verifiability. We find that asking experts to provide scores for these three aspects resulted in each sighting being considered more individually. Additionally, since the heavy reliance on the choice of prior can often be the downfall of Bayesian methods, we use an informed prior which changes with time.

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Running Head: "I tawt I taw a puddy tat!": Extinction and uncertain sightings of the Barbary lion

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Abstract

As species become rare and approach extinction, purported sightings can be controversial, especially when scarce management resources are at stake. We report a Bayesian model where we consider the probability that each individual sighting is valid. Obtaining these probabilities clearly requires a strict framework to ensure that they are as representative as possible. We used a process, which has proven to provide accurate estimates from a group of experts, to obtain probabilities for the validation of 35 sightings of the Barbary lion. We considered the scenario where experts are simply asked whether a sighting was valid, as well as when we asked them to score the sighting based on distinguishablity, observer competence, and verifiability. We find that asking experts to provide scores for these three aspects resulted in each sighting being considered more individually. Additionally, since the heavy reliance on the choice of prior can often be the downfall of Bayesian methods, we use an informed prior which changes with time.

Keywords: critically endangered, data quality, extinction, IUCN Red List, possibly extinct, sighting record, sighting uncertainty

1 Introduction

As a species approaches extinction, sightings become increasingly infrequent and questioned (Sibley et al. 2006). Since rare species are often observed sporadically, each sighting is rare and can greatly affect how conservation measures are applied (Roberts et al. 2010). Time since last sighting is an important component when assessing the persistence of a species (Solow 2005; Butchart et al. 2006), however the exact timing of the last sighting itself may be uncertain due to the quality of sightings towards the end of a record (Jarić & Roberts 2014). Incorrect declaration of extinction is not

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uncommon. Scheffers et al. (2011) identified 351 rediscovered species over the past 122 years (104 amphibians, 144 birds, and 103 mammals). Alternatively a species could persist indefinitely in a state of purgatory as Critically Endangered (Possibly Extinct), thus incurring the costs associated with this status (McKelvey et al. 2008) - for example the Ivory-billed Woodpecker (*Campephilus principalis*), see Roberts et al. (2010), Dalton (2010), Jackson (2006) and Collinson (2007).

Several models have been developed to infer extinction based on a sighting record (see Solow, 2005 for a review). However, it is has not uncommon to find examples (Cabrera 1932; Mittermeier 1975; Wetzel et al. 1975; Snyder 2004) where the perceived acceptability, authenticity, validity or veracity of a sighting is attributed to an assessment of the observer (e.g. local hunters, ornithologists, collectors, field guides) based upon an arbitrary judgement of a third party and/or a perception of the conditions under which the sighting was made, rather than a systematic consideration of the sightings record. Further, there is a risk that only Western scientists are perceived competent to find and save threatened species (Ladle et al. 2009) which implies that the input of informed others (usually locals) is not valued.

Not only is there a need for an objective framework evaluating ambiguous sightings (McKelvey et al. 2008; Roberts et al. 2010), a method to incorporate these assessments into the analysis of a sighting record is also required (Roberts et al. 2010). Recently, several studies have developed methods of incorporating sighting uncertainty within the analysis of a sighting record (Solow et al. 2012; Thompson et al. 2013; Jarić & Roberts 2014; Lee et al. 2014; Lee 2014), with the most recent methods assigning probabilities of reliability to individual sightings (Jarić & Roberts 2014; Lee et al. 2014). Here we extend this approach by first presenting an objective framework for quantifying the reliability probabilities using methods of eliciting expert opinion (Burgman et al. 2011; McBride et al. 2012). Second, we incorporate this sighting reliability (using basic rules of probability)

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into the well-established Bayesian model (Solow 1993), which assumes that all sightings are certain. These methods are then applied to the sighting record of the extinct North African Barbary lion (*Panthera leo leo*) for which a considerable amount of sighting data has recently been amassed from Algeria and Morocco (Black et al. 2013). The quality of these sightings varies from museum skins, to oral accounts elicited many years after the original sighting, some of which have proved controversial. Understanding the sighting behaviour and extinction time of lions in North Africa will help inform the conservation of other fields, particularly the now critically endangered West African lion populations.

The Barbary or Atlas lion of North Africa, ranged from the Atlas Mountains to the Mediterranean (the Mahgreb) during the 18th century. However, extensive persecution in the 19th century reduced populations to remnants in Morocco in the west, and Algeria and Tunisia in the east. The last evidence for the persistence of the Barbary lion in the wild is widely considered to be the animal shot in 1942 on the Tizi-n-Tichka pass in Morocco's High Atlas Mountains (Black et al. 2013). However, later sightings have recently come to light from the eastern Mahgreb that push the time of last sighting to 1956. Previous analysis of these sighting records (where all sightings are considered valid) suggest that Barbary lions actually persisted in Algeria until 1958, ten years after the estimated extinction date of the western (Morocco) population (Black et al. 2013).

2 Method

2.1 The expert estimates

Determining the probability that a sighting is true is very challenging there are many factors and nuances which generally require experts to interpret how they influence the reliablity of a sighting. We used expert opinion to determine a probability that each sighting is true. First, experts were asked the straightforward question "What is the

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probability that this sighting is of the taxon in question?" (Q1). Then, to encourage experts to explicitly consider the issues surrounding identification, we asked three additional questions:

(Q2) How distinguishable is this species from others that occur within the area the sighting was made? Note that this is not based on the type of evidence you are presented with, i.e. a photo or a verbal account.

(Q3) How competent is the person who made the sighting at identifying the species, based on the evidence of the kind presented?

(Q4) To what extent is the sighting evidence verifiable by a third party?

Responses to Q2, Q3 and Q4 provide a score for distinguishablity D, observer competency O and verifiability V respectively. We define the probability that a sighting is true as the average of these three scores,

$$P(true) = \frac{1}{3}\big(D + O + V\big), \tag{1}$$

where $D, O, V \in [0, 1]$. We acknowledge that this definition of $P(true)$ is not exact, however it seems intuitive that it would, at the very least, be closely related to the probability that a sighting is true. We now describe in detail what should be considered when allocating the scores.

Distinguishability score, D: that the individual sighting is identifiable from other taxa. This requires the assessor to consider other species within the area a sighting is made and, and question how likely is it that the taxa in question would be confused with other co-occurring taxa. In addition to the number of species with which the sighting could be confused, one should also take into consideration the relative population abundance in this estimate. For example, suppose there is video evidence which possibly shows a particular endangered species. But the quality of the video is such that it is uncertain whether the

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video has captured the endangered species, or a similar looking species which is more common. Based on say, known densities, home range size, etc, one could give this video a score of 0.2 - that is for every individual of the endangered species, there would be four of the more common species.

Observer competency score, O: that the observer is proficient in making the correct identification. This requires the assessor to determine the ability of the observer to distinguish the taxon from other species. This may be the ability of the observer to correctly identify the species they observe (e.g. limited for a three second view of a bird in flight), or the assessor's own ability to identify the species from a museum specimen. Care should be taken to avoid favouring one observer over another.

Verifiability score, V: that the sighting evidence could be verified by a third party. This requires the assessor to determine the quality of the sighting evidence. For example a museum specimen or a photograph would score highly whereas a reported sighting where there is no evidence other than the person's account would have a low score. Nonetheless, a recent observation has the opportunity for the assessor to return to the site and verify the sighting. As one can tell, there is not a prescribed system.

In the Barbary lion example we asked five experts to provide responses to Q1 (Eq. 1), and Q2–Q4 (D, O and V), using the methods proposed by Burgman et al. (2011) and McBride et al. (2012). All available information was provided for the last 35 alleged sightings of the Barbary lion (Supplementary material 1). Using this information, the experts responded to each question with a value between 0 and 1 (corresponding to low and high scores) for each sighting. We refer to this value as the 'best' estimate. Additionally, for each question, experts provided an 'upper' and 'lower' estimate, and a confidence percentage (how sure the expert was that the 'correct answer' lay within their upper and lower bounds). These estimates were then collated, anonymised and then provided to the experts for subsequent discussion of the results. These collated estimates, along with the information

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previously provided, were then discussed in a meeting of the experts, after which each person privately provided revised estimates for each of the four questions. These final estimates were used to assign average estimates of reliability for each of four scores (Eq. 1, D, O and V) for each sighting (Supplementary material 2). The upper and lower bounds were extended (if necessary) so that all bounds represented 100% confidence that the 'correct answer' lay within. For example, an expert may state that s/he is 80% confident that the 'correct answer' is between 0.5 and 0.9. We extend the bounds to represent 100% confidence, that is, 0.4 and 1. Finally all experts were asked to anonymously assign a level of expertise to each of the other experts from 1 being low to 5 being high. These scores were used as a weighting so that reliability scores from those with greater perceived expertise had more influence in the model.

2.2 The model

Suppose there are S certain sightings over a period of T years. A common approach to infer the probability that a species is extinct E from the data $\boldsymbol{s}$ is Solow's Bayesian formula (Solow, 1993),

$$P(E|\underline{s}) = 1 - \left(1 + \frac{1-\pi_t}{\pi_t B(\underline{s})}\right)^{-1} \quad \text{where} \quad B(\underline{s}) = \frac{S-1}{(T/T_N)^{S-1} - 1}, \tag{2}$$

and π_t is the prior belief that the species is extant at time t, T_N is the date of the last sighting and $S \geq 2$. However, this formula does not include uncertain sightings. Let $\boldsymbol{u} = (u_1, u_2, \ldots u_i \ldots, u_N)$ represent N uncertain sightings with corresponding probabilities of being true, $\boldsymbol{t} = (t_1, t_2, \ldots t_i, \ldots, t_N)$.

From basic laws of probability, we include the N uncertain sightings in addition to the record of certain sightings, $\underline{s}$ (which contains $S \geq 2$ certain sightings). The process is described most easily by demonstrating with one uncertain sighting: $\boldsymbol{u} = u_1$. The

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probability of extinction is

$$P(E|\underline{s}) = P(E|S)(1 - t_1) + P(E|S, u_1)t_1, \quad (3)$$

where t_1 is the probability of the uncertain observation being true (and hence $1 - t_1$ is the probability of it being false). This can be extended for numerous uncertain observations, $\boldsymbol{u} = (u_1, u_2, \ldots, u_N)$. Since we must consider all combinations of uncertain sightings being true and false, the number of terms on the right hand side of Eq. 3 is 2^N.

Here we define the probability of an uncertain sighting being true t_i by the process described in the previous subsection, where the 'best' estimate is our focus, and we consider it bounded by results from the 'upper' and 'lower' estimates. We examine responses to Q1, and the average of responses to Q2–Q4.

2.2.1 The choice of prior

As with all Bayesian methods, this model is sensitive to the choice of prior. Typically, it is challenging to form a prior belief that the species is extant/extinct, so an uniformed prior is used. However, choosing an arbitrary prior for a Bayesian method can provide misleading results (Efron, 2013).

Before the last sighting, $t = T_N$, the prior belief that the species is extant, π_t, is 1. After T_N, the prior is commonly taken to be 0.5, provided no other information is available. However, this results in a posterior probability that will quickly approach $P(E|\underline{s}) = 1$ (certain extinction) when sightings are absent. Bayes' formula has this property when one of the hypotheses (extinct/extant) fully accounts for the data (extinction means no sightings), and we have no additional information to set the prior (Alroy, 2014).

In this work we consider the prior described by Alroy (2014). That is, the prior probability of extinction during any time interval is determined by an exponential decay process, and

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there is a 50% chance a species has gone extinct by the end of its observed range,

$$1 - e^{-\mu T_N} = 0.5, \tag{4}$$

where μ is the cessation rate, and can be calculated for a given T_N. The prior at time $t = T_N + 1$ is

$$\overline{\pi}_{T_N+1} = 1 - \pi_{T_N+1} = \frac{\epsilon}{\epsilon + (1-\epsilon)(1-p_s)}, \tag{5}$$

where $\epsilon = 1 - e^{-\mu}$, and p_s is the probability of a sighting (assuming no false sightings),

$$p_s = \frac{S-1}{T_N - 2}. \tag{6}$$

More generally, for $t \geq T_N + 2$,

$$\overline{\pi}_t = 1 - \pi_t = \frac{\pi_{t-1} + (1-\pi_{t-1})\epsilon}{\pi_{t-1} + (1-\pi_{t-1})\epsilon + (1-\pi_{t-1})(1-\epsilon)(1-p_s)}. \tag{7}$$

The prior belief that the species is extinct decreases at each non-sighting iteration. To observe the prior function, let us assume for a moment that all the observations are valid. The prior function begins at T_N with a value of 0, and increases to 1 by an 'S' shape (Fig. 1). This seems more intuitive than a constant value. The prior does not reach 0.5 (the constant value typically chosen) until 1954 for the Moroccan sightings, and 1966 for the Algerian sightings, and when the sightings are combined. This means that choosing a constant prior of 0.5 after the last sighting, would provide a greater extinction probability before 1954/1966, and a lower extinction probability afterwards.

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2.3 Comparing with Lee et al. (2014)

The Bayesian model of Lee et al. (2014), implemented in Winbugs, also formally includes uncertain sightings. This model requires one sighting record comprising of certain observations, and then uncertain records are grouped according to their reliability. Sightings of a particular reliability comprise a parallel sighting record, thus providing several parallel uncertain sighting records. For example, suppose the sighting record is over seven years with a certain sighting in year 1 and 4, and uncertain sightings with 0.8 probability of being true ($t_i = 0.8$) in years 2, 5 and 6, and an uncertain sighting with 0.4 probability of being true ($t_i = 0.4$) in year 7. Our model considers the validity of the four uncertain sighting individually and then considers all possible combinations of the uncertain sightings being true or false ($2^4 = 16$ combinations). Conversely, the method of Lee et al. (2014) focus on the rate of certain and uncertain sightings so uses these data in the form

$$\underline{s}_1 = (1,0,0,1,0,0,0),\ \underline{s}_2 = (0,1,0,0,1,1,0),\ \underline{s}_3 = (0,0,0,0,0,0,1),\ \underline{s}_4 = (0,0,0,0,1,0,1). \quad (8)$$

To use the method of Lee et al. (2014), we assume that the two most certain observations are in fact certain, comprising s_1. The uncertain observations are grouped according to the best estimate (from the weighted average of Q2–Q4). Observations with best estimate 0.7–0.8, 0.6–0.7 and 0.5–0.6 were considered as three other uncertain sighting records, s_2, s_3, s_4. Since each record needs the same set of estimates, the best estimate was taken as the average of the best estimates within that sighting record. Similarly the upper and lower bounds are the average of the upper and lower bounds of observations within that sighting record.

We considered the extinction probability only at the time of the last sighting (whether certain or uncertain) and in 2014, and did not use the Alroy prior. We used an unbiased prior belief that the Barbary lion is extant of $\pi_{T_N} = 0.5$ for both times. To highlight any

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effects of the prior, for 2014 we also used a prior of $\pi_T = 0.1$ (prior belief of extinction being 0.9).

3 Results from Barbary lion example

3.1 The expert estimates

The simplest definition for the certainty estimate t_i, $i = 1, 2, \ldots, N$, is the average of the 'best' estimates of Q1. Alternatively, as discussed in the previous section, we take the average of Q2–Q4. Responses to Q1 remain close to the median of $\tilde{t} = 0.81$, whereas taking the average of Q2–Q4 resulted in a bigger range (this is the range when outliers are excluded, but they were included in the analysis), Fig. 2. A large range of reliability over the varying observations is expected. As such, perhaps the low range around $\tilde{t} = 0.81$ for Q1 is a sign of question fatigue.

When simply asked whether the sighting was correct (Q1), the responses are very similar to whether the sighting was distinguishable (Q2), see Fig. 2. That is, left undirected, experts place most emphasis on distinguishability (Q2) when deciding whether a sighting is valid. It appears that the additional two questions about observer competency (Q3) and verifiability (Q4) made the experts consider the sighting more sceptically, lowering the average median to $\tilde{t} = 0.66$. Therefore, because the Barbary Lion is a highly distinguishable species, each sighting is biased toward being more reliable than perhaps warranted. This illustrates the effect of considering different elements which make a sighting reliable.

When the estimates for expertise are included, the estimates increase for all questions. Hence, those perceived as qualified experts have more faith in each sighting. To include this variation in expertise, and because considering distinguishability (Q2), observer competency (Q3) and verifiability (Q4) separately provides more range over sightings, we

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present results from the average of weighted Q2 to Q4 only (Av.Q2–Q4(w)).

3.2 The model

To use the model, we treat the two sightings with the highest 'best' estimate as certain sightings. Note that choosing the certain sightings in this manner is not ideal. There can be as little as 0.001 difference between the second and third best estimate (Algeria, Table 3a), yet one of these sightings is treated as 'certain'. Additionally, due to model restrictions, only the most reliable sighting is used in any given year.

We applied the model to the Algerian and Moroccan sightings combined, and then to the locations separately. Before discussing the results from these three cases, we discuss some general features of the output.

The probability that the species is extinct is zero until the later of the two certain sightings (denoted by T_N). Note that this may be falsely predicting the species is extant to a more forward date; nonetheless, the chances of this are small when the highest 'best' estimates are close to one.

After T_N, the probability that the species is extinct rises, with drops at the uncertain sightings. After a drop, the extinction probability increases with a steeper gradient for the 'high' estimates (from upper bounds on reliability provided by experts), and less steep for the 'low' estimates (from lower bounds on reliability provided by experts). This is because, for the high estimates, the model is expecting a fairly good sighting regularly, so the effect of no sighting is more influential than in the 'low' case. When two sightings occur close together in time, the combined result can be as strong as a single, more certain sighting. The size of the drop also depends on when the sighting occurred. This is because the effect of any sighting depends non-linearly upon the sighting record preceding it (including the uncertain sightings that occur before T_N), which also explains why the probability of extinction using the 'best' estimate does not always lie between the lower and upper

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estimates. Nonetheless, at the occurrence of each sighting, the estimates have the expected order on the extinction probability; that is, the 'high' estimate (from the upper bound on reliability) corresponds to the lowest probability of extinction.

3.2.1 Combined sightings

When the two populations are combined (Algeria and Morocco), there were 21 sightings in non-repeating years. The two sightings with the highest 'best' estimate occurred in 1917 and 1925, meaning that we assume the lion was extant in 1925. From 1925 to 1949 eight (uncertain) sightings occurs, creating regular drops which maintain the chance of extinction below 0.2. The extinction probability increases rapidly when the time between sightings exceeds six years (between 1949 and 1956). This is because prior to 1925 there were 10 uncertain sightings, with at most six years between sightings (between 1905 and 1910), see Table 2. However, the 1956 sighting creates a significant drop in extinction probability so that in 1956 the extinction probability is 0.38. But how does this probability change when the sightings are separated by population?

3.2.2 Separate populations

A lion observation occurred during 14 different years in Algeria, and 12 different years in Morocco, see Tables 3a and 3b. The mean 'best' reliability estimate for Algeria is 0.6797 and for Morocco is 0.6779. That is, the sightings are practically as reliable in Algeria as in Morocco. However, the lions were reported on two more occasions in Algeria (this is also true if multiple sightings from the same year are included). Additionally, the lion was possibly observed as recently as 1956 in Algeria, compared with 1942 in Morocco. The 1942 Moroccan sighting is assumed certain so the lion is assumed to be extant, whereas in Algeria there was a $\sim$ 0.1 extinction probability. Algeria experienced three uncertain sightings after 1942 (1943, 1949 and 1956) which Morocco did not. Therefore, by 1956 the lion was now more likely to be extinct in Morocco than Algeria. This ordering continued

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until after 2000, when both populations of the lion are presumed extinct.

The latest sighting in Algeria was 1956, while the latest Morocco sighting was in 1942. The latest Moroccan sighting has a 'best' estimate of 0.775, meaning it is only slightly more reliable than the 1956 sighting in Algeria which has a 'best' estimate of 0.763. However, the 1956 Algerian sighting is the third most reliable from that population, while the 1942 Moroccan sighting is the second most reliable, consequently the Moroccan sighting is assumed certain, meaning the Barbary lion could not be extinct prior to 1942 (Fig. 3c). The Algerian extinction probability would also be zero until the last sighting if the 1956 Algerian sighting scored a slightly larger 'best' estimate (or the 1911 sightly scored slightly less). In fact, the 1911 and 1956 Algerian sightings have similar reliabilities, and by not weighting the experts by experience, the 1956 sighting actually is the second most reliable sighting, see Table 1a. This reiterates that choosing uncertain sightings as certain can lead to bias, and is only appropriate when experts generally agree that they are very likely to be valid. Despite there being slight disagreement with the exact ordering of the top two sightings, there is agreement amongst the questioning (and averaging) methods that the chosen 'certain' sightings are amongst the most reliable sightings with high reliability probabilities (see Tables 1a–2).

3.3 Comparing with Black et al. (2013) and Lee et al. (2014)

Black et al. (2013) concluded that the Barbary lion went extinct in Algeria in 1958, with an upper bound of 1962 (95% confidence interval). In comparison, our model provides a low extinction probability of 0.082 in 1958 (with bounds of 0.026 and 0.276). Even in 1962, which is the upper bound (95% confidence interval) provided by Black et al. (2013), our work provides a relatively low extinction probability of 0.147 (with bounds of 0.085 and 0.346), see Fig. 3b. However, when comparing the Moroccan extinction date, Black et al. (2013) provide an upper bound of 1965, whereas the method here provides an extinction probability of 0.882 (with bounds of 0.658 and 0.978). Nonetheless,

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this probability is the result of a steep incline since 1948, which is Black et al.'s (2013) predicted extinction date. Our method gives an extinction probability of merely 0.032 (with bounds of 0.022 and 0.047) in 1948, see Fig. 3c.

To compare our work with the method of Lee et al. (2014), we calculated the extinction probability at two times only: the time of the last sighting and 2014. For the purposes of this comparison, we did not use the Alroy prior, but instead used an unbiased prior belief that the Barbary lion is extant of $\pi_{T_N} = 0.5$ for both times; and an additional comparison from using a prior of $\pi_T = 0.1$ (prior belief of extinction being 0.9) for 2014.

There is not great disagreement between the two methods, especially when considering the current (2014) probability that the lion is extinct, (Fig. 4). The main difference is that our method is not as heavily influenced by the prior. This is most clearly seen when considering the extinction probability in 2014 under a 0.5 prior belief that the species is extant - the extinction probability is considerably closer to 0.5 when using the method of Lee et al. (2013), despite a sighting not occurring for decades.

4 Discussion

In recent years there have been several extinction models that consider uncertainty of sightings in their calculations (Solow et al. 2012; Thompson et al. 2013; Jarić & Roberts 2014; Lee et al. 2014; Lee 2014). However, uncertain sightings are generally classed together (e.g. Solow et al, 2012), or grouped into smaller sub-groups based on degree of certainty (Lee et al. 2014). We present a Bayesian extinction model that allows each sighting to be scored based on expert opinion.

Within this model we used a prior belief of extinction that varies with time, as described by Alroy (2014). Bayesian methods can rely heavily on a prior belief, and often this is chosen to be 0.5, a seemingly unbiased value. However, using a Bayesian method with an

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uninformed prior can provide misleading results (Efron 2013; Alroy 2014). Further, the method presented here appears less influenced by the prior than the Bayesian method of Lee et al. (2014).

Not only do current extinction models generally gloss over the choice of a prior, they also gloss over the process of defining the probability that an uncertain sighting is valid. There is a clear need to establish a formal framework to determine the reliability of sightings during assessments of extinction.

In the case of the Barbary lion, experts tended to provide estimates in the region of 0.81 when asked the probability that the sighting in question was of a Barbary lion. The score is similar to those given when discussing distinguishability. This may suggest that when considering sightings of the Barbary lion the overriding factor is distinguishablity. To reduce the problem of one factor (such as distinguishability) overriding the other issues, a formal framework that considers observer competence and the time of evidence (verifiability) is therefore required.

This framework may also reduce acrimony among observers who cannot provide verifiable supporting evidence. The suggested method to uses group discussion, but ultimately experts provide their score in private. The scores can be aggregated in an unbiased manner or weighted so that the opinion of the more experienced carries more influence.

Lastly, over time, the extinction probability output could enable decision-makers to forge a link between the process of sighting assessment and the process of concluding survival or extinction. The method is therefore less arbitrary than present methods such as decisions made on the basis of a vote by experts or a final conclusion by the most senior expert. Furthermore, by identifying a probability, decision-makers are better able to apply the precautionary principle (Foster et al. 2000) on a data-informed basis rather than subjective assessment of available information.

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Table 1: The top six most reliable sightings (locations separated) under different definitions of 'reliability'. The sightings which we consider certain are highlighted in bold.

(a) Algerian sightings.

Reliability	Q1	Q1(w)	Q2–Q4	Q2–Q4(w)
1	**1911**	**1911**	**1917**	**1917**
2	1920	**1917**	1956	**1911**
3	**1917**	1920	**1911**	1956
4	1912	1912	1935	1935
5	1956	1935	1920	1920
6	1935	1910	1910	1910

(b) Moroccan sightings.

Reliability	Q1	Q1(w)	Q2–Q4	Q2–Q4(w)
1	**1925**	**1925**	**1925**	**1925**
2	1895	1895	**1942**	**1942**
3	1911	1920	1911	1900
4	1920	1911	1900	1911
5	1917	**1942**	1930	1930
6	**1942**	1900	1895	1895

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Table 2: All sightings with the weighted low, high and best estimates of the reliability probability, averaged over Q2–Q4. When more than one sighting occurred in the same year, the sighting with the highest 'best' estimate was used. The two sightings with the highest 'best' estimate were assumed to be certain (1917 and 1925). The dashed line separates sightings occurring before the last certain sighting (1925) and those after. The 'A' indicates an Algerian sighting, and 'M' indicates a Moroccan.

Population	Year	Low	High	Best
A	1917	0.680	0.954	0.849
M	1925	0.762	1.000	0.931
M	1895	0.424	0.891	0.665
A	1898	0.367	0.886	0.648
M	1900	0.500	0.923	0.729
M	1901	0.433	0.828	0.658
A	1905	0.355	0.834	0.616
A	1910	0.453	0.915	0.694
A	1911	0.536	0.930	0.764
A	1912	0.534	0.921	0.688
A	1920	0.491	0.954	0.714
M	1922	0.318	0.808	0.563
A	1929	0.425	0.806	0.638
M	1930	0.507	0.878	0.670
A	1934	0.383	0.873	0.594
A	1935	0.549	0.964	0.762
M	1939	0.311	0.790	0.580
M	1942	0.582	0.962	0.775
A	1943	0.316	0.839	0.533
A	1949	0.334	0.868	0.651
A	1956	0.465	0.908	0.763

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Table 3: Sightings with the weighted low, high and best estimates, averaged over Q2–Q4. When more than one sighting occurred in the same year, the sighting with the highest 'best' estimate was used.

(a) The two sightings with the highest 'best' estimate were assumed to be certain (1911 and 1917). The dashed line separates sightings occurring before the last certain sighting (1917) and those after.

Year	Low	High	Best
1911	0.536	0.930	0.764
1917	0.680	0.954	0.849
1898	0.367	0.886	0.648
1905	0.355	0.834	0.616
1910	0.453	0.915	0.694
1912	0.534	0.921	0.688
1920	0.491	0.954	0.714
1929	0.425	0.806	0.638
1930	0.406	0.816	0.602
1934	0.383	0.873	0.594
1935	0.549	0.964	0.762
1943	0.316	0.839	0.533
1949	0.334	0.868	0.651
1956	0.465	0.908	0.763

(b) The two sightings with the highest 'best' estimate were assumed to be certain (1925 and 1942). All other sightings occurred before the 'certain' sighting in 1942.

Year	Low	High	Best
1925	0.762	1.000	0.931
1942	0.582	0.962	0.775
1895	0.424	0.891	0.665
1900	0.500	0.923	0.729
1901	0.433	0.828	0.658
1911	0.507	0.902	0.729
1917	0.449	0.906	0.632
1920	0.347	0.856	0.613
1922	0.318	0.808	0.563
1930	0.507	0.878	0.670
1935	0.322	0.898	0.590
1939	0.311	0.790	0.580

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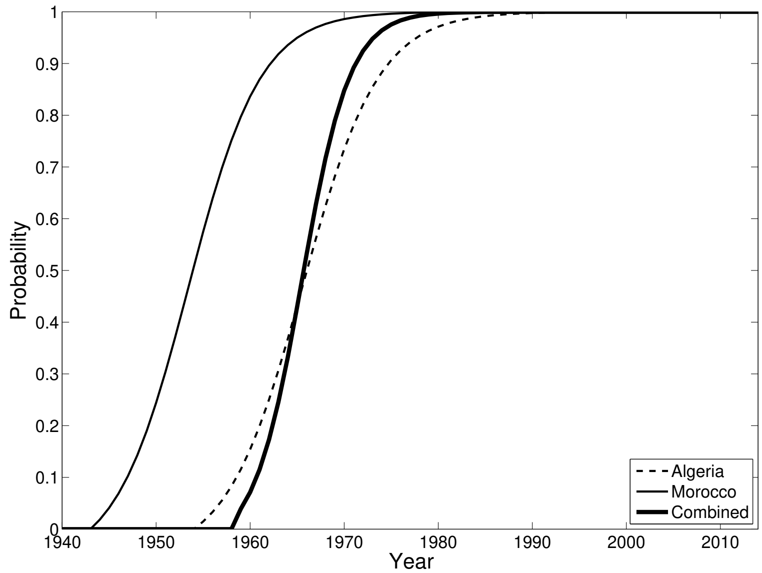

Figure 1: The prior belief that the Barbary lion is extinct, assuming all sightings are valid.

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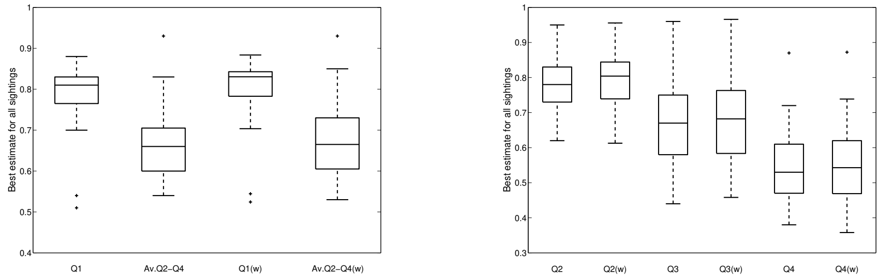

(a) Question 1 and the average of Question 2 to 4.

(b) Question 2 (distinguishability), Question 3 (observer competence) and Question 4 (verifiability).

Figure 2: The distribution of 'best' estimates, where the middle line marks the median over the sightings, the box represents the interquartile range, and the whiskers provide the range, excluding outliers. Each statistic is given first in its unweighted form, then after giving more weight to more qualified experts.

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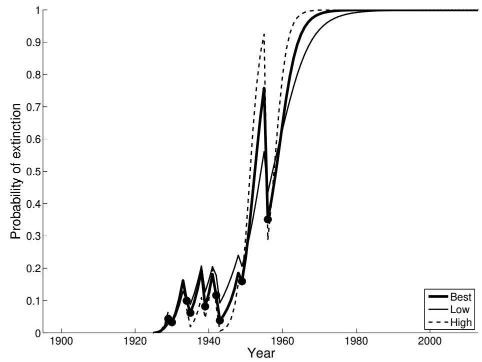
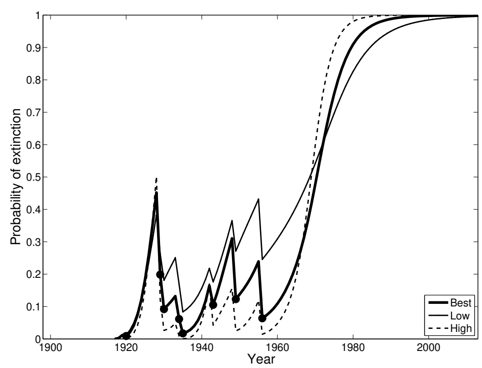
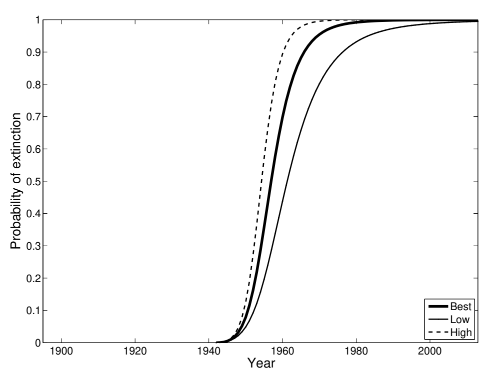


(a) Algerian and Moroccan sightings combined. The uncertain sightings are in 1929, 1930, 1934, 1935, 1939, 1942, 1943, 1949 and 1956.



(b) Algerian sightings only. The uncertain sightings are in 1920, 1929, 1930, 1934, 1935, 1943, 1949 and 1956.



(c) Moroccan sightings only. There were no sightings after the 'certain' sighting in 1942.

Figure 3: Estimated probability that the Barbary lion is extinct over time. Each circle marks the weighted average from the expert's 'best' estimate (Q2–Q4) for the uncertain sightings.

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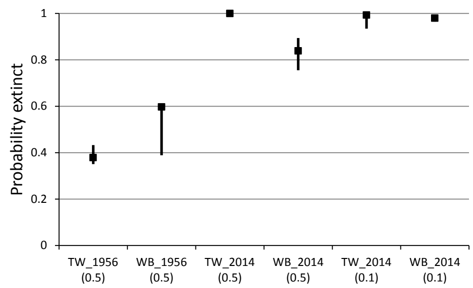
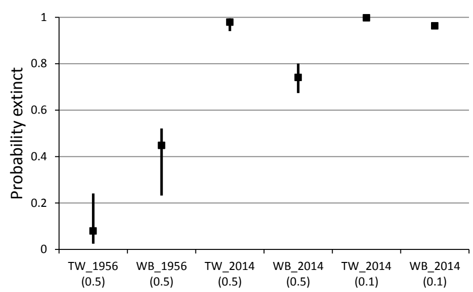
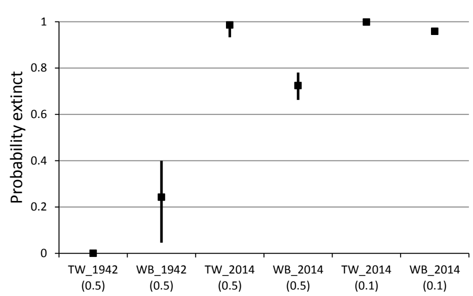


(a) Populations combined (last possible sighting in 1956).



(b) Algeria (last possible sighting in 1956).



(c) Morocco (last possible sighting in 1942).

Figure 4: Comparing this work (TW) with Lee et al. (2014) (WB). We consider the extinction probability at the time of the last possible sighting (prior belief that the lion is extant of 0.5) and in 2014 (with prior belief that the lion is extant of 0.5 and 0.1).

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Figure 1(on next page)

The prior belief that the Barbary lion is extinct, assuming all sightings are valid.

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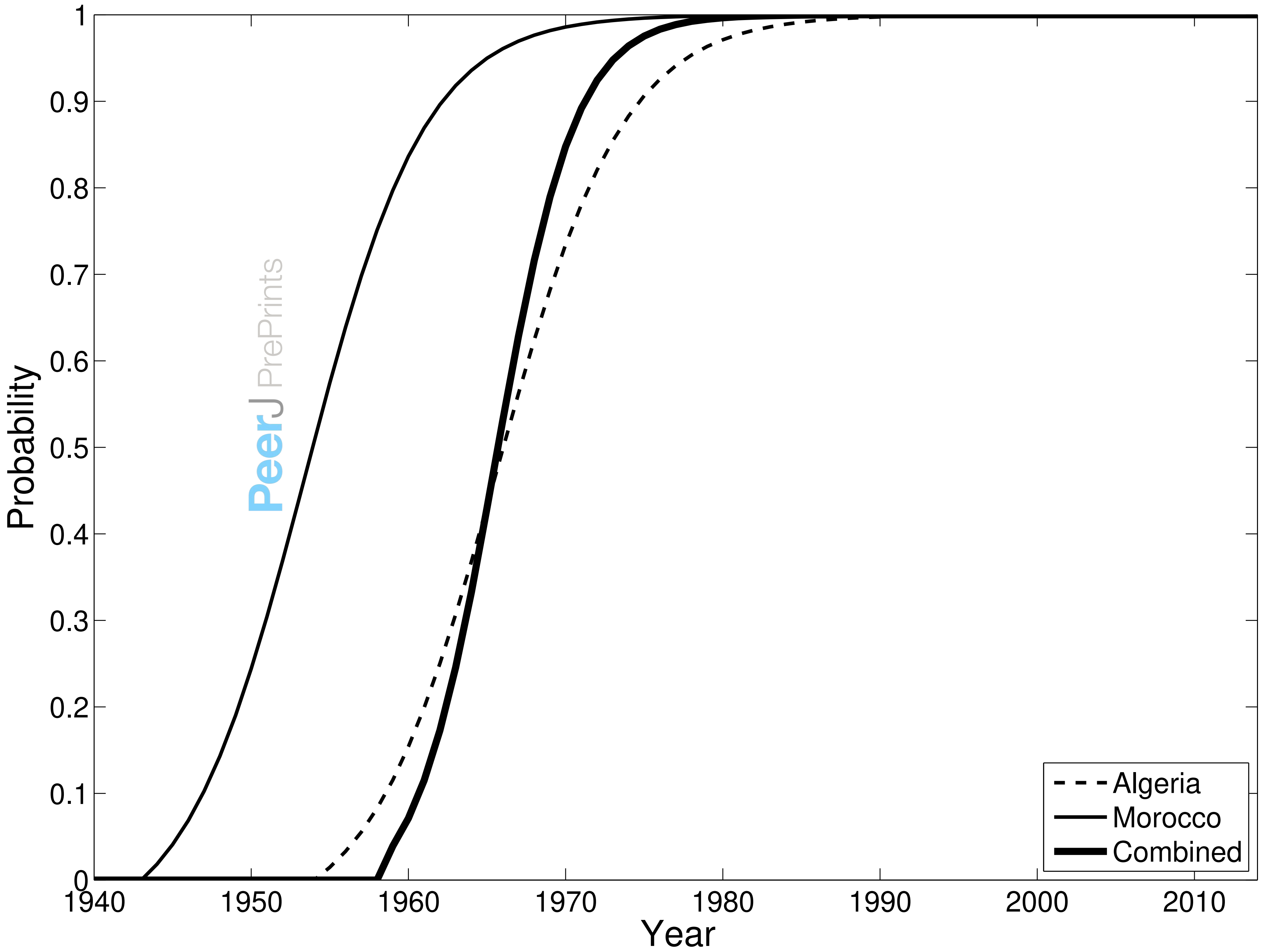

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Table 1 (on next page)

Figure 2a - The distribution of ‘best’ estimates using standard box plots. Each statistic is given first in its unweighted form, then after giving more weight to more qualified experts.

(a) Question 1 and the average of Question 2 to 4.

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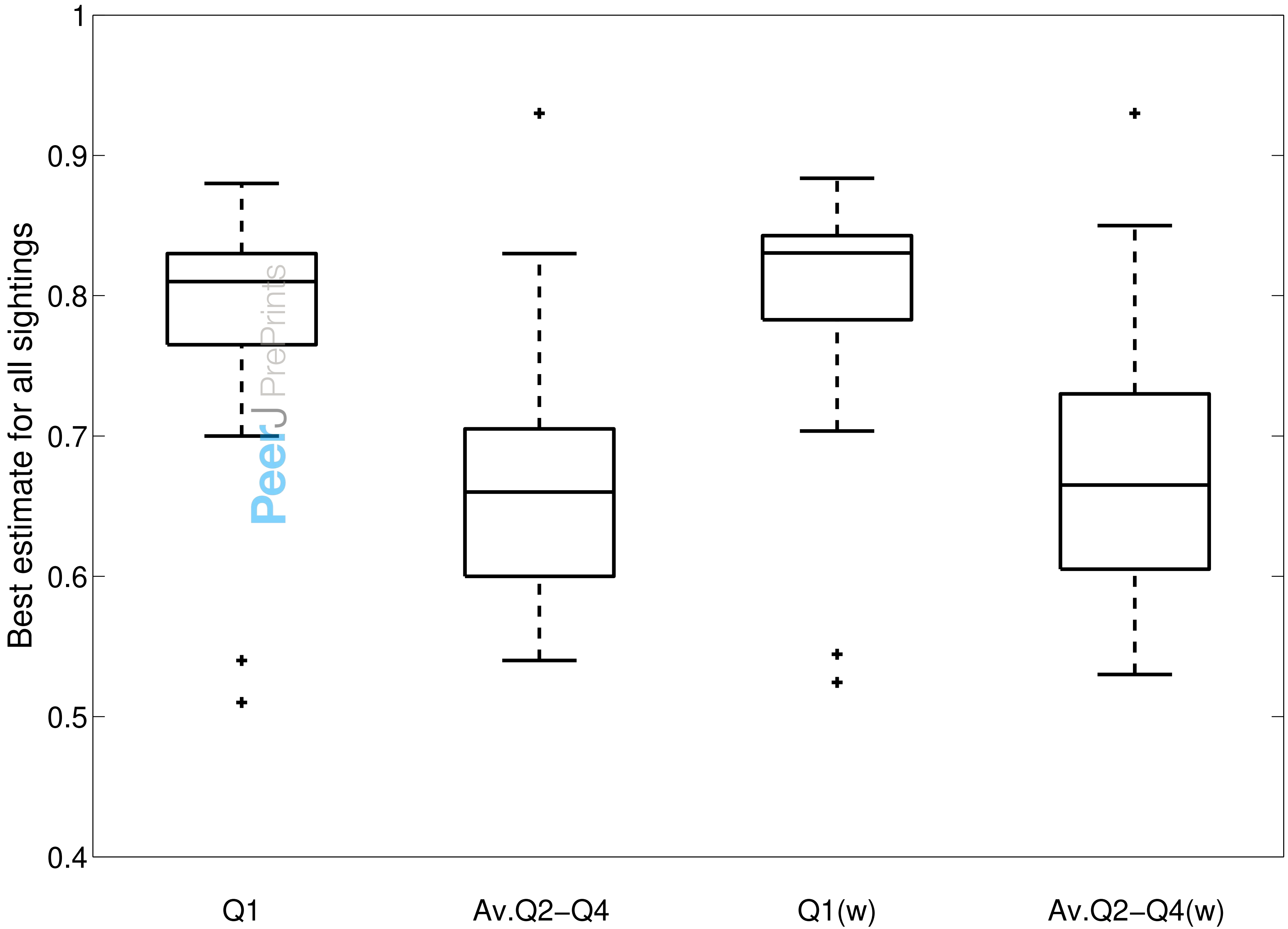

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Figure 2(on next page)

Figure 2b -The distribution of ‘best’ estimates using standard box plots. Each statistic is given first in its unweighted form, then after giving more weight to more qualified experts.

(b) Question 2 (distinguishability), Question 3 (observer competence) and Question 4 (verifiability).

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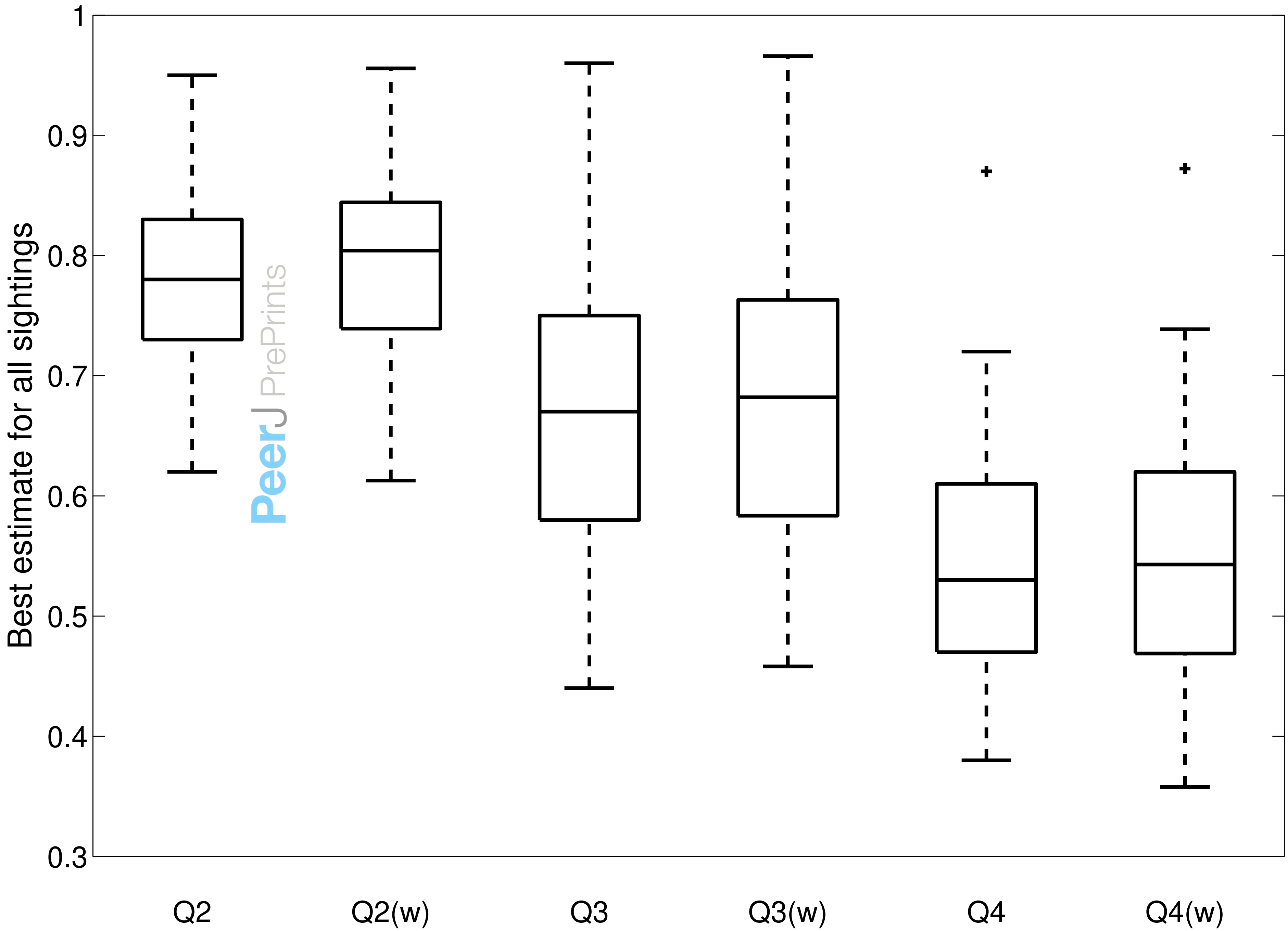

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Figure 3(on next page)

Figure 3a - Estimated probability that the Barbary lion is extinct over time. Each circle marks the weighted average from the expert's 'best' estimate (Q2–Q4) for the uncertain sightings.

(a) Algerian and Moroccan sightings combined. The uncertain sightings are in 1929, 1930, 1934, 1935, 1939, 1942, 1943, 1949 and 1956.

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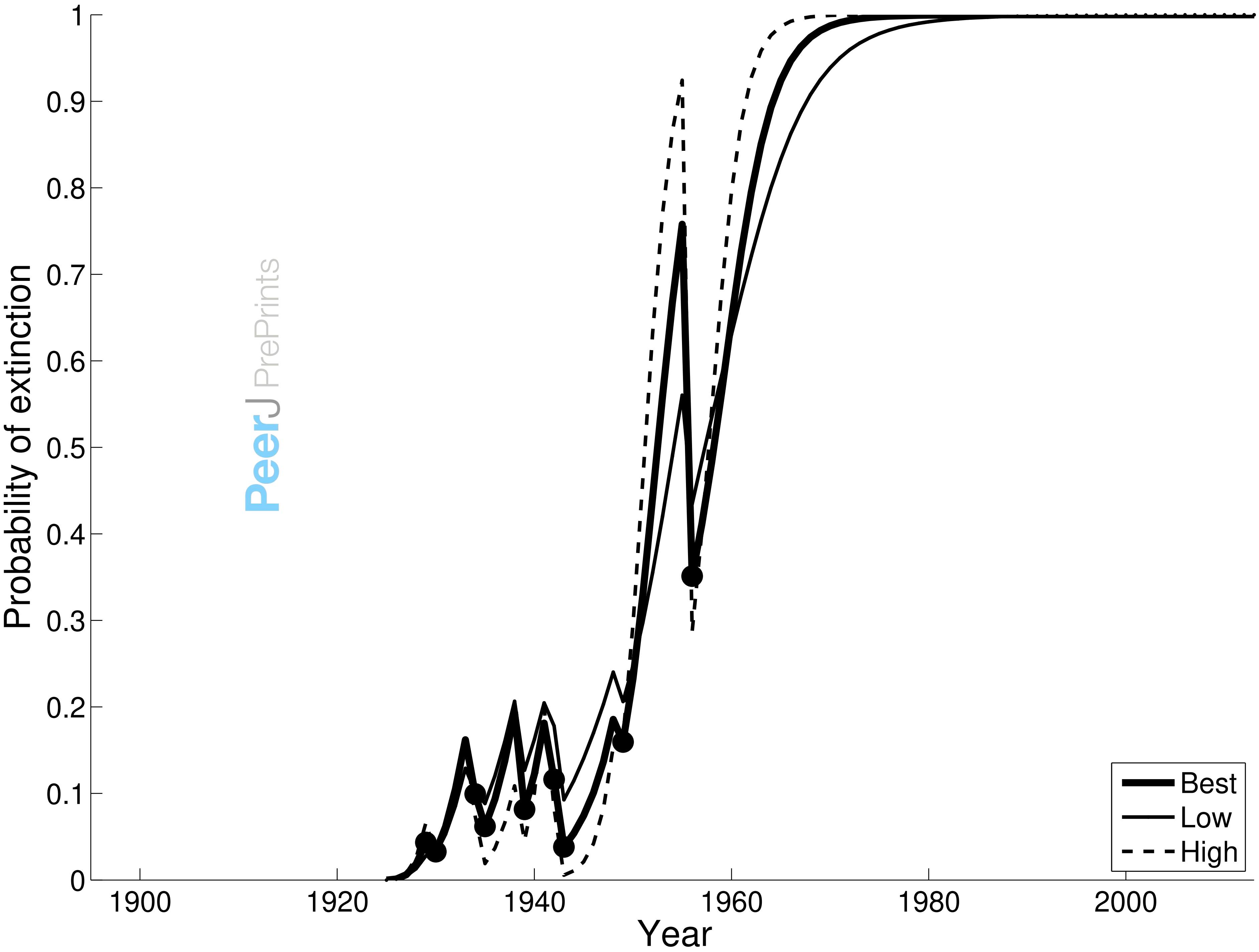

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Figure 4(on next page)

Figure 3b - Estimated probability that the Barbary lion is extinct over time. Each circle marks the weighted average from the expert's 'best' estimate (Q2–Q4) for the uncertain sightings.

(b) Algerian sightings only. The uncertain sightings are in 1920, 1929, 1930, 1934, 1935, 1943, 1949 and 1956.

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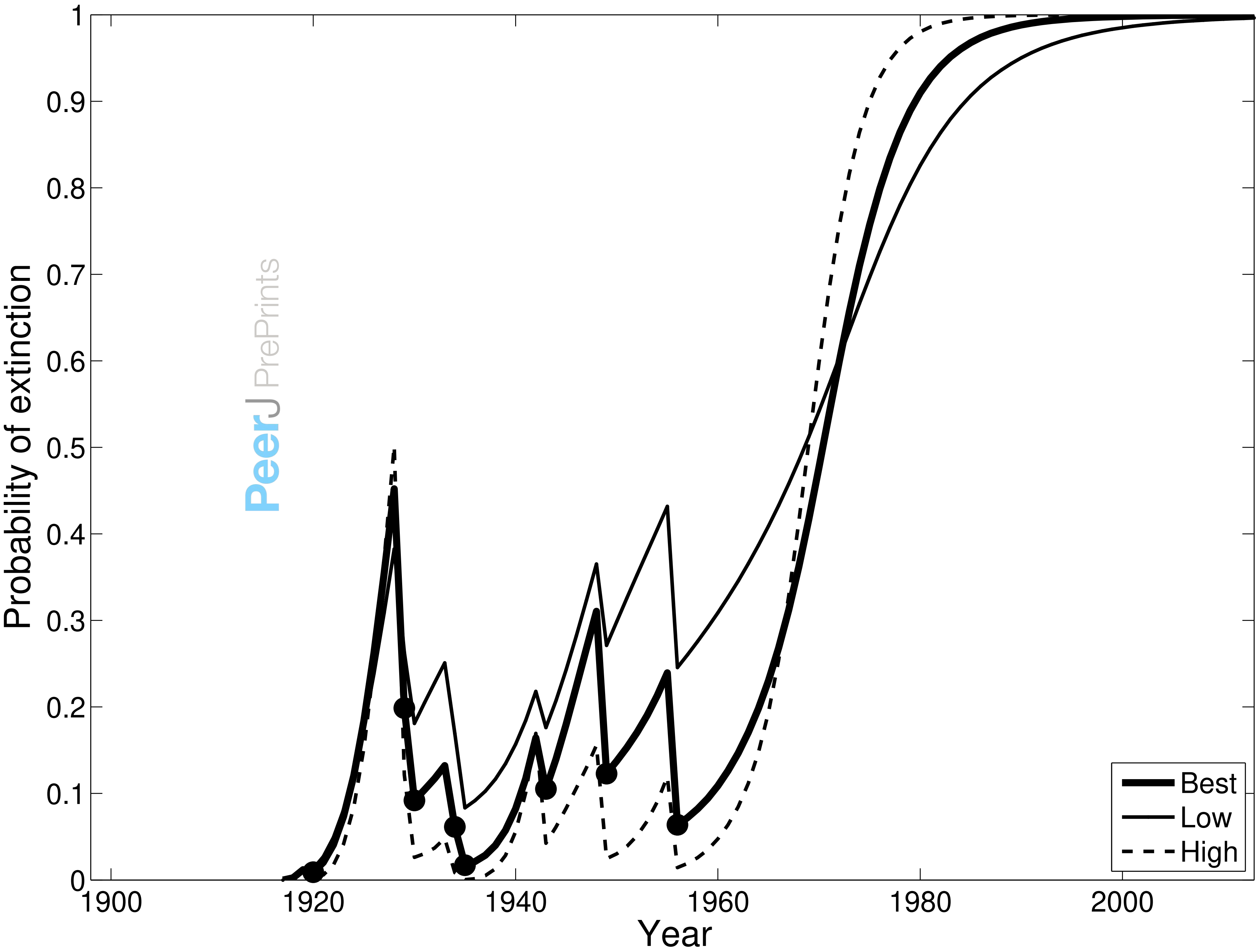

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Figure 5(on next page)

Figure 3c - Estimated probability that the Barbary lion is extinct over time. Each circle marks the weighted average from the expert's 'best' estimate (Q2–Q4) for the uncertain sightings.

(c) Moroccan sightings only. There were no sightings after the 'certain' sighting in 1942.

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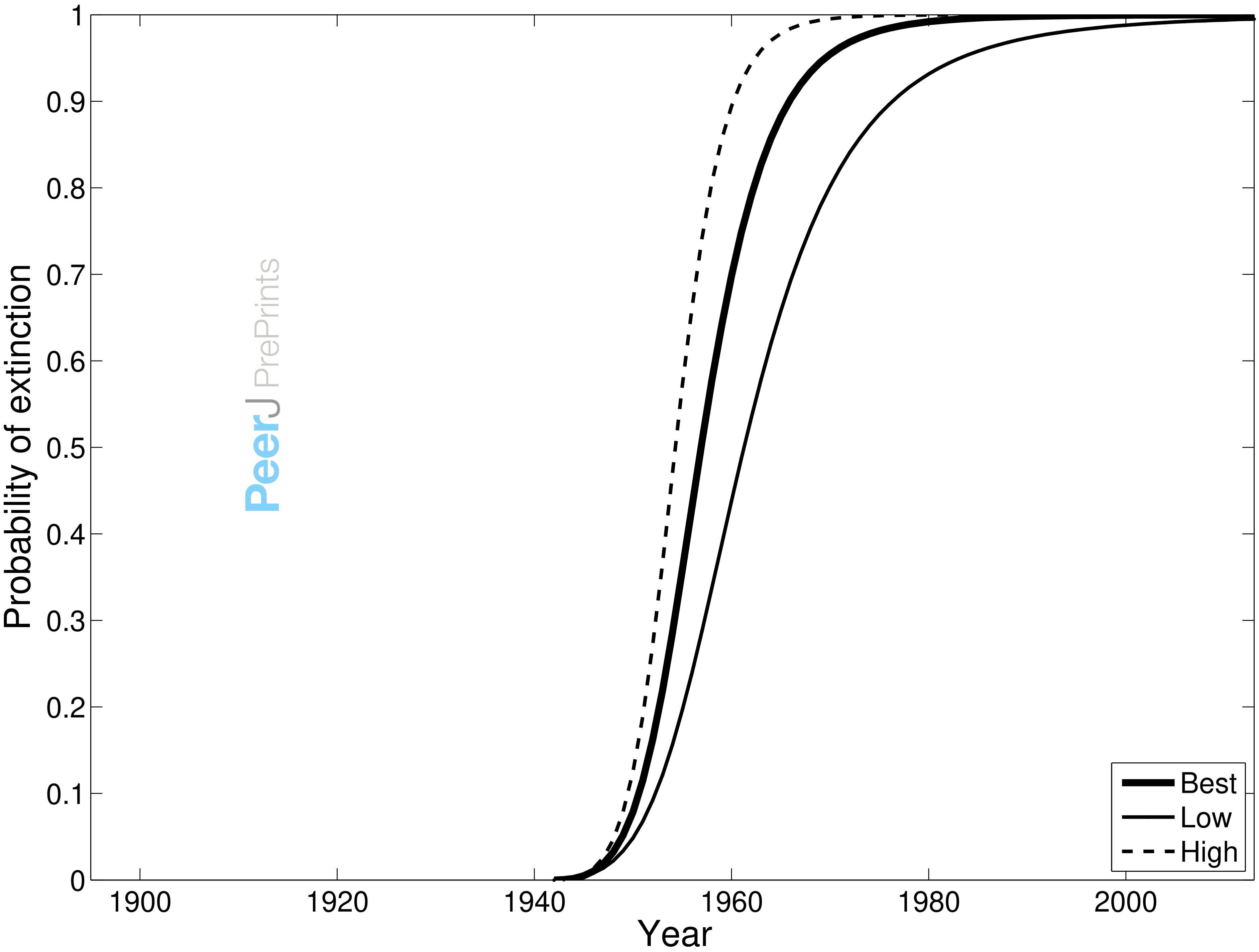

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Figure 6 (on next page)

Figure 4a - Comparing this work (TW) with Lee et al. (2014) (WB). We consider the extinction prob. at the last possible sighting (prior extant belief of 0.5) and in 2014 (with prior extant belief of 0.5 and 0.1).

(a) Populations combined (last possible sighting in 1956).

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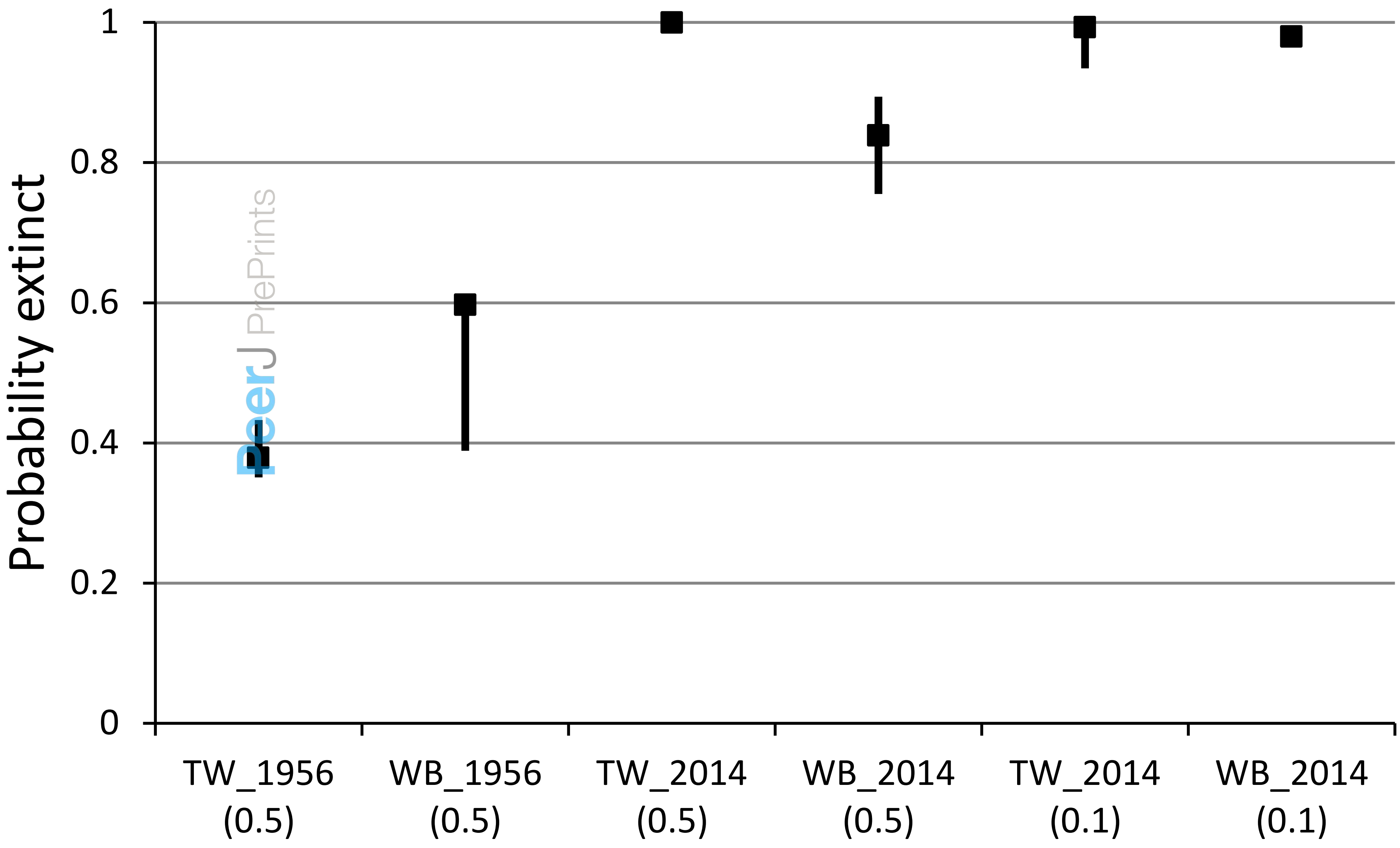

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Figure 7 (on next page)

Figure 4b - Comparing this work (TW) with Lee et al. (2014) (WB). We consider the extinction prob. at the last possible sighting (prior extant belief of 0.5) and in 2014 (with prior extant belief of 0.5 and 0.1).

(b) Algeria (last possible sighting in 1956).

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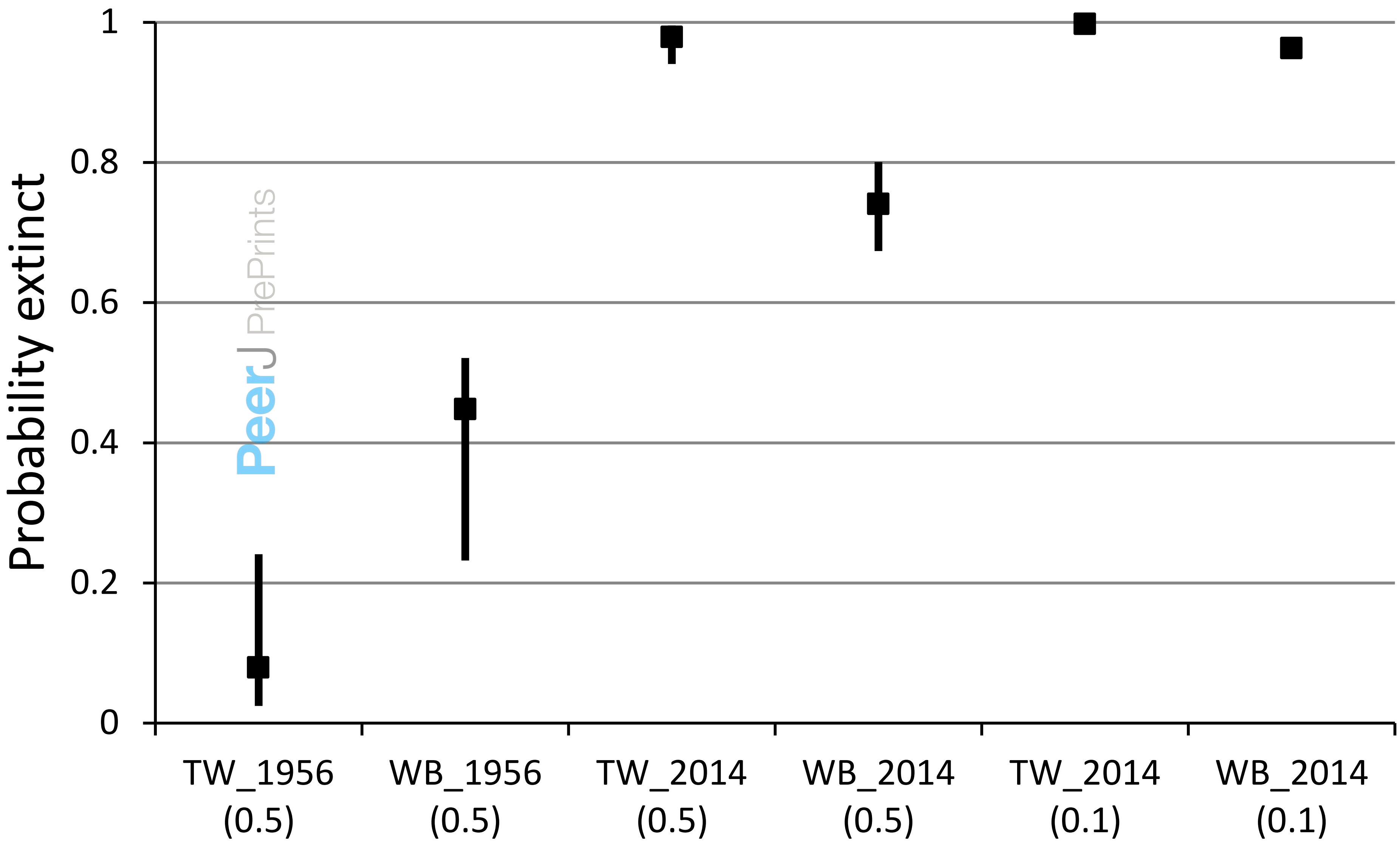

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Figure 8(on next page)

Figure 4c - Comparing this work (TW) with Lee et al. (2014) (WB). We consider the extinction prob. at the last possible sighting (prior extant belief of 0.5) and in 2014 (with prior extant belief of 0.5 and 0.1).

(c) Morocco (last possible sighting in 1942).

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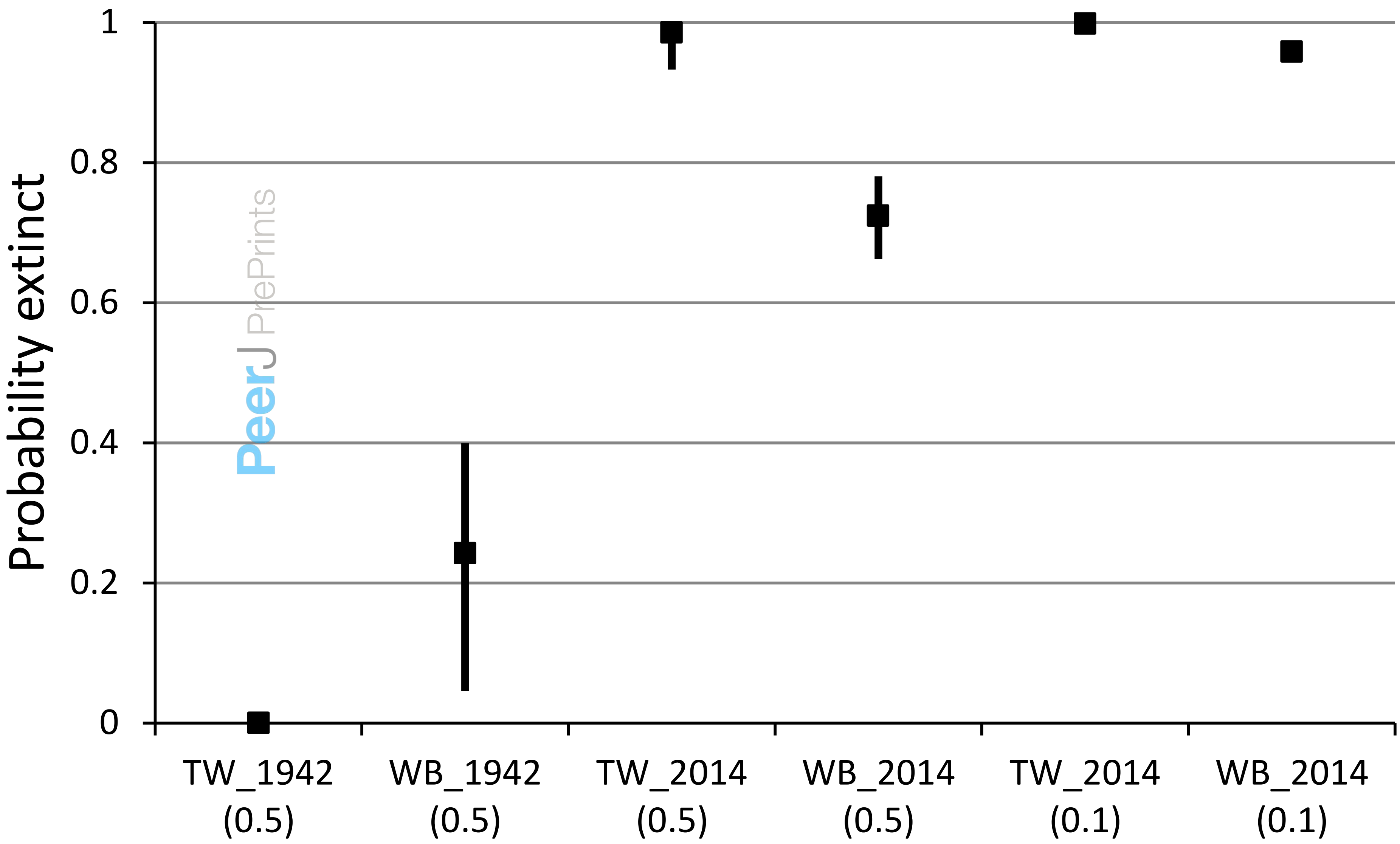

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