Detecting and quantifying parasite-induced host mortality from intensity data: method comparisons and limitations

Mark Q. Wilber*, Sara B. Weinstein, Cheryl J. Briggs

Department of Ecology, Evolution and Marine Biology, University of California, Santa Barbara, Santa Barbara California, United States of America

*Corresponding author. Mark Q. Wilber, Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, 2111 Noble Hall, Santa Barbara, CA 93106, USA
E-mail address: mark.wilber@lifesci.ucsb.edu

Note: Supplementary data associated with this article

17 **Abstract**

18 Parasites can significantly impact animal populations by changing host behavior, reproduction and survival.
19 Detecting and quantifying these impacts is critical for understanding disease dynamics and managing wild animal
20 populations. However, for wild hosts infected with macroparasites, it is notoriously difficult to quantify the fatal
21 parasite load and number of animals that have died due to disease. When ethical or logistical constraints prohibit
22 experimental determination of these values, examination of parasite intensity and distribution data may offer an
23 alternative solution. In this study we introduce a novel method for using intensity data to detect and quantify
24 parasite-induced mortality in wildlife populations. We use simulations to show that this method is more reliable than
25 previously proposed methods while providing quantitative estimates of parasite-induced mortality from empirical
26 data that are consistent with previously published qualitative estimates. However this method, and all techniques that
27 estimate parasite-induced mortality from intensity data alone, have several important assumptions that must be
28 scrutinized before applying those to real-world data. Given that these assumptions are met, our method is a new
29 exploratory tool that can help inform more rigorous studies of parasite-induced host mortality.

30

31 *Keywords:* Parasite aggregation, Negative binomial distribution, Crofton Method, Host survival function, Lethal
32 dose

33

1. Introduction

Infectious agents can impact animal populations by changing population dynamics and stability (Dobson and Hudson, 1992; Tompkins et al., 2002), altering predator-prey interactions (Joly and Messier, 2004), and even causing species' decline and extinction (De Castro and Bolker, 2005; McCallum, 2012). Accurately estimating the impact of these infectious agents in wildlife is critical to understanding what regulates host and parasite populations, making predictions about disease transmission and managing disease outbreaks (Langwig et al., 2015). The impact of pathogens such as rabies (Coyne et al., 1989), bovine tuberculosis (Cox et al., 2005) and rinderpest (Tillé et al., 1991), are typically modeled based on the presence or absence of disease, such that host survival is not generally considered to be a function of the number of infectious agents present within the host. In contrast, models of macroparasites generally assume that pathology increases with parasite burden and host survival probability must be treated as a function of infection intensity (Anderson and May, 1978). Helminths exhibiting this intensity-dependent pathology have significant impacts on human health (Brooker et al., 2004), domestic livestock economics (Roeber et al., 2013) and wildlife survival (Kirk, 2003; Logiudice, 2003). While it is generally assumed that some fraction of wild host populations succumb to parasitic infection, it is notoriously difficult to actually quantify parasite-induced host mortality (PIHM) in wild animal populations because it is difficult to observe the dead or dying hosts most impacted by parasitism (McCallum, 2000).

Ideally, PIHM is quantified by experimentally infecting and tracking individual hosts in the wild population; however, for logistical and ethical reasons this method is rarely feasible (McCallum, 2000). Snapshot data of parasite intensities across multiple hosts is much easier to collect and has often been used to identify the presence of PIHM (Crofton, 1971; Lester, 1977, 1984; Lanciani and Boyett, 1989; Royce and Rossignol, 1990; Ferguson et al., 2011), and to quantify the relationship between infection intensity and host mortality (Adjei et al., 1986).

Crofton (1971) first proposed that PIHM could be identified from parasite intensity data by comparing the observed parasite distribution in sampled hosts with the distribution predicted in the absence of parasite-induced mortality. This method assumes that, prior to host mortality, infection intensity in the host population follows a negative binomial distribution and the tail of the distribution is truncated as intensity-dependent pathology removes

the most heavily infected hosts. Assuming mortality occurs only in heavily infected hosts, evidence of this parasite-induced mortality should then be detectable by iteratively fitting a negative binomial distribution to hosts with lower and lower parasite intensities, and comparing these truncated predicted distributions with the corresponding truncated observed parasite data (Fig. 1, see Supplementary Data S1.1 for additional detail).

While the Crofton Method detects the presence of PIHM, it makes no attempt to quantify the relationship between infection intensity and host survival probability; information that is necessary for estimating parasite impacts on host populations (Anderson and May, 1978; Tompkins et al., 2002). Adjei et al. (1986) suggested that this relationship could be calculated by first using the Crofton Method to estimate the pre-mortality parasite distribution and then using this distribution to calculate the probability of host survival with increasing parasite intensity. To do this, Adjei et al. (1986) modeled host survival as a logistic function and then used a generalized linear model (GLM) to estimate the parameters of the host survival function (see Supplementary Data S1 for a technical description of the Adjei Method). Although this method can predict the host survival function, it has several technical drawbacks. When mean infection intensity is high or sample sizes are small, the observed intensity data must be subjectively binned into intensity ranges in order to fit the GLM framework. Furthermore, for the Adjei Method to work, any observed intensity values greater than predicted values must be modified and set equal to the predicted values (see Supplementary Data S1 for details); a questionable act of data manipulation. These manipulations may introduce bias, reduce the precision and limit the power of this method to detect and quantify parasite-induced host mortality.

After 30 years, and despite clear limitations (McCallum, 2000), these methods (particularly the Crofton Method) are still discussed among parasitologists and are the primary techniques for examining population-level impacts of parasitism using parasite intensity data. In these methods, PIHM can only be identified by visually examining plots of the pre-mortality parameters predicted by the Crofton Method and determining whether they show a “kink” over a range of truncation values (Fig. 1B; Lester, 1984; Ferguson et al., 2011). These qualitative criteria make it difficult to compare PIHM between studies and a more rigorous and quantitative method is needed to both detect and quantify host mortality. The survival function given by the Adjei Method may be used to do this; however, it requires manipulation of the original data and its accuracy remains untested.

In this study, we propose a novel method for detecting and quantifying PIHM that ameliorates many of the aforementioned deficiencies of the previous methods. Our method does not require data alteration, is highly generalizable and uses standard statistical techniques to quantitatively determine whether PIHM is occurring in a system. We use simulations to compare our method with the Adjei Method to test the ability of both to (i) detect occurrence of PIHM and (ii) estimate the host survival function. We then apply both methods to real datasets previously used in PIHM analyses and compare the results. Finally, we discuss the limitations of inferring PIHM from intensity data and how these methods fit in modern quantitative parasitology.

2. Materials and methods

2.1. A novel, likelihood-based method for estimating PIHM

Our method (henceforth the Likelihood Method) begins with the same assumptions as the Adjei Method: namely that infection has occurred and hosts with fatal parasite loads have died prior to the population sampling. As discussed by Adjei et al. (1986), this is not necessarily unrealistic as some parasite infections occur primarily in younger hosts with parasite-induced mortality occurring soon after infection (e.g. Schotthoefer et al., 2003; Johnson and McKenzie, 2008).

The Likelihood Method then assumes that prior to mortality the parasite distribution can be described by the distribution $g(x; \phi)$, which specifies the probability of a host having x parasites before mortality occurs. ϕ is a vector of parameters that describes the shape of this distribution. The probability of a host surviving with x parasites from infection until sampling is given by the host survival function $h(\text{survival}; x, \theta)$ where θ specifies any additional parameters needed to define the host survival function.

With these two assumptions, we can define a distribution that gives the probability of having a parasite load of x parasites, conditional on host survival, $P(x|\text{survival})$. Using standard rules of conditional probability this distribution can be written as

$$P(x|\text{survival}) = \frac{P(\text{survival}|x) * P(x)}{P(\text{survival})}$$

(1)

$P(\text{survival}|x)$ is the survival function $h(\text{survival}; x, \theta)$, $P(x)$ is the pre-mortality parasite distribution

$$g(x; \phi) \text{ and } P(\text{survival}) = \sum_{x=0}^{\infty} P(\text{survival}|x) * P(x) = \sum_{x=0}^{\infty} h(\text{survival}; x, \theta) * g(x; \phi).$$

Therefore, equation 1 can be written as

$$P(x|\text{survival}) = \frac{h(\text{survival}; x, \theta) * g(x; \phi)}{\sum_{x=0}^{\infty} h(\text{survival}; x, \theta) * g(x; \phi)}$$

Using this probability distribution, one can then find the parameters θ and ϕ that maximize the likelihood of an observed host-parasite dataset. To estimate the significance of PIHM in a host-parasite system, a likelihood ratio test can be used in which the full model is given by equation 2 and the reduced model is given by the pre-mortality distribution $g(x; \phi)$. If PIHM is not significant in the system, the resulting likelihood ratio statistic should approximately follow a χ^2 distribution with degrees of freedom equal to the number of parameters in the full model with parasite-induced mortality minus the number of parameters in the reduced model without parasite-induced mortality (Bolker, 2008).

The parameterization of equation 2 depends on the parasite system of interest. Here, we assume that the pre-mortality parasite distribution $g(x; \phi)$ follows a negative binomial distribution with two parameters, mean parasite intensity (μ_p) and aggregation (k_p , where smaller k_p indicates a more aggregated parasite population) before mortality (Crofton, 1971; Anderson and May, 1978; Adjei et al., 1986). A variety of different biological and statistical assumptions can result in an equilibrium parasite distribution that follows a negative binomial distribution (Kendall, 1948; Boswell and Patil, 1970; Calabrese et al., 2011). Furthermore, the negative binomial distribution is

an incredibly flexible distribution that fits many host-parasite systems even when the underlying mechanisms determining the empirical distribution are unknown (Shaw et al., 1998).

The function for $h(\text{survival}; x, \theta)$ is also system specific. Many theoretical models of parasite-induced host mortality assume that the parasite-induced death rate of hosts is a linear function of parasite intensity (Anderson and May, 1978; Dobson and Hudson, 1992; Barbour and Pugliese, 2000). In systems where there is truly a linear relationship between infection intensity and survival probability it will be nearly impossible to use intensity data to detect parasite-induced host mortality (Lanciani and Boyett, 1989). However, some systems do exhibit non-linear host survival functions (Benesh, 2011), in which case these methods would be applicable.

To compare the Likelihood Method and the previously proposed Adjei Method, we adopt the non-linear, logistic host-survival function used in the earlier study given by

$$h(\text{survival}; x, a, b) = \frac{\exp(a - b \log(x))}{1 + \exp(a - b \log(x))}$$

(3)

Generally, a larger b leads to a more rapid decline in the probability of host survival as parasite intensity increases, with the maximum rate of decline having a value of $b/4$ (Supplementary Data S1). b is in many ways analogous to the pathogenicity parameter (α) in classic macroparasite models that gives the parasite intensity-dependent host death rate (Anderson and May, 1978; Isham, 1995). When b is held constant, a larger a allows for hosts to tolerate larger parasite intensities before experiencing parasite-induced mortality. More specifically, for every one unit increase in a , the log parasite intensity at which any percentage of hosts survive (e.g. 99% of hosts survive) increases by $1/b$ (Supplementary Data S1).

The equation $\exp(a/b)$ can also be used to calculate the parasite LD_{50} , here defined as the infection intensity above which a host has greater than 50% probability of dying. Equation 3 is commonly used in toxicology

and has the useful properties of being bounded between 0 and 1 and being differentiable for all x (Collet, 2002). That being said, it is phenomenological and is used simply because it tends to fit survival data. However, given that a goal of these analyses is to compare the results from the Likelihood Method with the Adjei Method, it is natural to adopt the same host-survival function to facilitate comparison. When applying the Likelihood Method to other systems, more mechanistic host-survival functions can be used in place of equation 3.

2.2. Evaluating the Adjei and Likelihood Methods

2.2.1. Question 1: can we detect PIHM?

We used statistical power and Type I error to test the ability of the Adjei Method and the Likelihood Method to correctly identify the presence of PIHM on simulated data with known pre-mortality parameters. The power of a method is the probability of correctly detecting PIHM, given that it is occurring, and the Type I error is the probability of incorrectly identifying PIHM, given that it is not occurring. If a method has low Type I error we can be confident that when we detect PIHM, it is actually occurring. If one method has a higher power for detecting PIHM than another, we will need to sample fewer hosts to detect PIHM.

Consistent with the model assumption that parasite infection, host mortality and population sampling are temporally separate events, we first created a pre-mortality host population by drawing N_p randomly infected hosts from a negative binomial distribution with parameters μ_p and k_p . This represents a host population that has become infected but not yet experienced parasite-induced mortality (Adjei et al., 1986). In the Adjei Method and Crofton Method, N_p is a necessary parameter defined as the number of hosts in the population before parasite-induced mortality. More accurately, N_p is the number of hosts that would have been sampled had parasite-induced host mortality not occurred. This parameter is not necessary when using the Likelihood Method because, unlike the Adjei Method and Crofton Method which estimate parasite-induced mortality using absolute numbers of hosts, the Likelihood Method estimates parasite-induced mortality using probabilities. However, to compare the results of the Likelihood Method with the Adjei Method, we specified a value for N_p for all simulations.

We next chose values of a and b for the host survival function and calculated the probability of survival for all N_p hosts using equation 3. Then, to simulate the period in which hosts died due to infection, for each host we drew a random number from a uniform distribution between 0 and 1 and if the calculated host survival probability was less than this random number, the host experienced parasite-induced mortality. The surviving individuals represent the post-mortality hosts that would be sampled in the field.

We then used these simulated pre-mortality and post-mortality datasets to test the ability of both methods to correctly determine whether or not PIHM was occurring when the parameters N_p , μ_p and k_p were known. Although the parameters N_p , μ_p and k_p are always unknown in real systems, a method that fails under these ideal simulation conditions with known parameters will certainly also fail when these values must be estimated from empirical data. In practice, for the Adjei Method, N_p , μ_p and k_p are estimated using the Crofton Method (Adjei et al., 1986), while μ_p and k_p in the Likelihood Method can be estimated jointly with a and b or via the Crofton Method.

We compared the two methods using three different mean parasite intensity values ($\mu_p = 10, 50, 100$) and three different host survival functions (gradual, moderate and steep decreases in the host survival with increasing parasite intensity, Fig. 2A). For a given μ_p , each survival function had the same LD_{50} ($\mu_p = 10$, $LD_{50} = 7.39$), ($\mu_p = 50$, $LD_{50} = 35.57$), ($\mu_p = 100$, $LD_{50} = 77.3$), but different values of a and b . We examined each μ_p survival function pair at three levels of parasite aggregation, $k_p = 0.1$, 0.5, and 1 — realistic values of parasite aggregation in natural populations (Shaw et al., 1998). For each of these 27 parameter combinations we simulated 150 datasets and tested the probability of each method correctly identifying PIHM in the post-mortality dataset (power) and incorrectly identifying PIHM in the pre-mortality dataset (Type I error). For each method, we used a likelihood ratio test to determine whether the full model with PIHM provided a significantly better fit than the reduced model without PIHM at significance level of 0.05. We also examined the impact of sample size by simulating each parameter for pre-mortality sample sizes of $N_p = (50, 100, 200, 300, 400, 500)$.

Wild host populations were assumed to be sampled after PIHM has occurred, thus we calculated the sample size in the power simulations as the average number of surviving hosts over all 150 simulations for each parameter combination. The distribution of surviving hosts over the 150 simulations was generally symmetrical and the S.D. was small compared with the mean (maximum coefficient of variation was approximately 0.06 across all parameter combinations), suggesting that the mean number of surviving hosts was an adequate summary statistic of the number of hosts sampled post-mortality.

We then tested the ability of the Likelihood Method to correctly identify PIHM under the more realistic condition of unknown pre-mortality parameters. Based on the first set of simulations, we excluded the Adjei Method and only examined the power of the Likelihood Method under “best-case” scenario parameter values, setting $\mu_p = 10$ and $k = 1$ because PIHM is most detectable when parasites are less clumped and mean intensity is low. We examined the impact of survival function shape and sample size on the ability of the Likelihood Method to identify PIHM when the pre-mortality parameters, μ_p and k_p , and the survival function parameters, a and b , needed to be estimated. We performed 500 simulations over a range of different samples sizes for gradual, moderate and steep survival functions, following the simulation procedure described above.

2.2.2. Question 2: can we estimate properties of the host survival function?

In the previous section we compared the ability of the Adjei Method and the Likelihood Method to provide a “yes” or “no” answer for whether or not PIHM was occurring in a system. In this section we compared the ability of the Adjei Method and the Likelihood Method to estimate properties of the survival function such as the parameters a , b and LD_{50} . Using the same simulation procedure and parameter combinations described above, we simulated 150 datasets, estimated a , b and LD_{50} , and calculated the standardized bias and precision for these estimates (Walther and Moore, 2005). Because estimating properties of the host survival function requires more information than simply detecting PIHM, we used larger values of N_p for this simulation ($N_p = (300, 500, 1000, 2000, 5000, 7500, 10000)$). We used the average number of surviving hosts for each set of 150 simulated

datasets as our measure of sample size. Although both a and b are necessary to estimate LD_{50} , the two parameters showed similar patterns of bias and precision so we only show the results for a .

2.3. Application to real data

We tested the ability of the Adjei Method and the Likelihood Method to identify PIHM in six host-parasite datasets given in Crofton (1971) and four datasets given in Adjei et al. (1986) (Table 1). Crofton (1971) analyzed infection patterns in the snail *Gammarus pulex* infected with the acanthocephalan *Polymorphus minutus*. Adjei et al. (1986) analyzed males and females of two species of lizard fish, *Saurida tumbil* and *Saurida undosquamis*, that were infected by the cestode *Callitetrarhynchus gracilis*.

In both earlier studies, the authors reported PIHM in some of the datasets and we tested whether the Adjei Method and/or the Likelihood Method also predicted PIHM. For the six datasets from Crofton (1971), we used the general conclusions of the author and truncated the data at four parasites, applied the Crofton Method to estimate the pre-mortality distribution, and then ran the Likelihood Method and Adjei Method using these pre-mortality parameters. For the Adjei et al. (1986) datasets, we followed the same procedure as the authors and first truncated the data at two parasites and then fit the Crofton Method for the female fish of both species. Then, following the methods of Adjei et al. (1986), we parameterized the male pre-mortality distributions for each species with the results from the females. Finally, we applied the Adjei Method and the Likelihood Method to determine whether or not PIHM was significant for these species and compared our results with those given by the authors. All code for the analyses can be found at https://github.com/mqwilber/parasite_mortality.

3. Results

3.1. Question 1: detecting presence of PIHM

The power of the Adjei Method to detect PIHM in a system was close to unity for larger sample sizes and tended to decrease as sample size decreased for all survival functions (Fig. 2C; Supplementary Figs. S1 - S3). The

Likelihood Method had a power close to unity for all parameter combinations and sample sizes considered. With gradual survival functions, the power of the Likelihood Method decreased slightly for small samples sizes (Fig. 2C, Supplementary Figs. S1 - S3).

The Adjei Method had highly inflated Type I error rates (i.e. falsely detected PIHM) for all parameter combinations that we considered (Fig. 2B; Supplementary Figs. S1 - S3). This method also showed the unintuitive pattern of decreasing Type I error rate with decreasing sample size. This occurred because, at small samples sizes, intensity data must be binned before the Adjei Method can be used (Supplementary Data S1). In contrast, the Likelihood Method showed a Type I error rate at or near the pre-set level of 0.05 for all parameter combinations and sample sizes considered (Fig. 2B; Supplementary Figs. S1 - S3).

When all parameters were jointly estimated, the Likelihood Method showed highly context-dependent results, even when detecting PIHM under the best-case scenario of $\mu_p = 10$ and $k_p = 1$. For steep survival curves, PIHM could be detected with a power of greater than 0.8 from a sample of less than 100 hosts (Fig. 3). However, for moderate survival functions over 400 hosts had to be sampled to achieve the same power and for gradual survival functions, no tested sample size ever achieved a power greater than 0.8 (Fig. 3).

3.2. Question 2: estimating the LD_{50} and survival function

The Likelihood Method gave asymptotically unbiased estimates of the LD_{50} for all combinations of parameters examined in this study (Fig. 4, Supplementary Figs. S4 - S6). Even for the smallest sample sizes we considered, the estimate of LD_{50} was largely unbiased when using the Likelihood Method, with small biases occurring for gradual host survival functions. The precision of the LD_{50} estimates decreased (increasing coefficient of variation) as sample size decreased for all parameter combinations we examined using the Likelihood Method (Fig. 4, Supplementary Figs. S4 - S6).

The Adjei Method produced biased estimates of the LD_{50} across nearly all parameter combinations,

tending to underestimate the true value of the parameter (Fig. 4, Supplementary Figs. S4 - S6). For $\mu_p = 10$, the LD_{50} estimates from the Adjei Method were largely unbiased for large samples sizes, but as μ_p increased, the Adjei Method produced biased estimates of LD_{50} across all sample sizes, with bias increasing as sample size decreased (Fig. 4, Supplementary Figs. S4 - S6). The LD_{50} estimates from the Adjei Method also showed large decreases in precision with the steepest survival function across all values of μ_p (Fig. 4, Supplementary Figs. S4 - S6).

In terms of the host survival function, the Likelihood Method gave unbiased estimates of survival function parameter a when sample sizes were large, however as sample size decreased these estimates became severely biased (Fig. 4, Supplementary Figs. S7 - S9). The Adjei Method produced biased estimates of the host survival function across all sample sizes, with consistently greater bias for steeper survival functions and higher mean parasite loads. (Fig. 4, Supplementary Figs. S7 - S9).

3.3. Application to real data

The previous authors qualitatively detected PIHM in seven of the 10 datasets considered (Table 1). The Likelihood Method parameterized from the pre-mortality parameters of the Crofton Method detected significant PIHM in six of these seven datasets at a significance level of 0.05. The only dataset in which the Likelihood Method did not detect a significant effect of PIHM was the Adjei dataset for female *S. tumbil*. For this dataset there was a marginally significant effect of PIHM ($\chi^2_{df=2} = 5.34; P = 0.069$). The Adjei Method detected PIHM in nine of the 10 datasets (Table 1), consistent with our simulation results showing that the Adjei Method has a high Type I error rate. Moreover, the Adjei Method estimates of the LD_{50} were quite variable for the Crofton data, consistent with our simulation results that the Adjei Method LD_{50} estimates could be imprecise for sample sizes of less than 1000 hosts (Supplementary Figs. S4 - S6).

4. Discussion

Our likelihood-based method to estimate PIHM from observed parasite intensity data is a significant improvement over the previous methods. In simulations, it had greater power for detecting PIHM over a wider range of parameter values and it also exhibited fewer false detection events (Type I errors) in both simulations and when applied to published datasets previously used in PIHM analyses. The Likelihood Method was also generally less biased and more precise when quantifying parasite-induced mortality via the host survival function for the parameters we considered. The superior performance of the Likelihood Method over the Adjei Method can be attributed to its fewer parameters, its lack of unnecessary data alteration, and its applicability across a variety of different parameter combinations. In short, the Likelihood Method is a better method for detecting and quantifying PIHM than the previously proposed Adjei Method.

Although superior to the Adjei Method, the Likelihood Method still cannot be applied to all real datasets. For host-parasite systems where host mortality occurs as a steep, non-linear function of parasite intensity, only 75 hosts must be sampled to have an 80% power in detecting PIHM. However, as the maximum slope of the survival function decreases and the function becomes somewhat linear, hundreds or possibly thousands of hosts would have to be sampled to achieve the same result. This is consistent with previous studies which illustrate the difficulty of detecting PIHM from linear host survival functions (Lanciani and Boyett, 1989). While it may be feasible to sample several hundred invertebrates or small fish, even the smallest sample sizes are completely unfeasible for many vertebrates, particularly the species of conservation concern where addressing the impact of parasitism would be most important. An even larger sample size would be required to identify PIHM when parasites are highly aggregated, mean infection intensity is high, or parasite prevalence is low, all of which are common in many parasitic helminths. Moreover, while linear functions make PIHM undetectable, at the other extreme, steep, non-linear survival curves produce severely biased estimates of the survival function. Given the interaction between all of these different factors, the Likelihood Method is probably limited to detecting PIHM in systems where greater than 100 hosts can be collected, parasites are common and only moderately aggregated, and substantial host mortality occurs at relatively low parasite intensity.

While we have improved on the existing methods for quantifying PIHM from parasite intensity data, all

such methods require several fundamental assumptions. Nearly all current methods derive from Crofton (1971) (but see Ferguson et al., 2011) and assume that, prior to any PIHM, parasites are distributed in the host population, following a negative binomial distribution. But it is fundamentally impossible to know what the pre-mortality parasite distribution was in a wild host population and it is widely recognized that different processes can lead to a variety of parasite distributions in hosts (Anderson and Gordon, 1982; Duerr et al., 2003). However, the negative binomial is extremely flexible and there is substantial empirical and theoretical evidence to support the assumption that, prior to any PIHM, parasite distributions can be fit by a negative binomial distribution (Shaw and Dobson, 1995; Shaw et al., 1998; Wilson et al., 2002).

It is important to note that the flexibility of the negative binomial distribution may also reduce our ability to detect PIHM. If a negative binomial can be fitted to the observed post-mortality parasite distribution then, regardless of how lethal the parasite was, it will be impossible to detect PIHM because there is no need for a more complex model. Many observed parasite distributions are well fitted by the negative binomial distribution (Shaw et al., 1998), suggesting that systems where these methods are applicable without any a priori knowledge may be uncommon. However, if one has a priori knowledge about some aspect of the pre-mortality distribution (e.g. assumes/knows the value of k_p , Ferguson et al., 2011), then the Likelihood Method could be applicable even if the post-mortality distribution was well fitted by a negative binomial.

If one has evidence that the pre-mortality is not a negative binomial, the generality of our method easily allows another distribution to be specified for $g(x, \phi)$. For example, one could use the resulting stationary host-parasite distribution from a stochastic host-parasite model without PIHM (Anderson and Gordon, 1982) to specify the form of $g(x, \phi)$ and then apply the techniques discussed in this paper to detect PIHM. The general requirement for the Likelihood Method to detect PIHM in a stochastic host-parasite process is that the stationary distribution of the process with mortality is significantly different from the stationary distribution without mortality. It is widely recognized that PIHM decreases the aggregation of host-parasite distributions relative to those without mortality (Barbour and Pugliese, 2000), suggesting that the Likelihood Method could be generally applicable to host-parasite systems that follow the assumptions of many stochastic host-parasite models. This is an intriguing area

for further research.

If the Likelihood Method is applicable and the truncation of the negative binomial distribution is detected, one must be aware that the truncation pattern may be caused by other processes such as within-host density dependence, age-dependent variation in host resistance and/or heterogeneous infection rates (Anderson and Gordon, 1982; Rousset et al., 1996; McCallum, 2000). This means that in the event that PIHM is detected, it may actually not be the result of PIHM. Moreover, if host mortality depends on parasite intensity and additional variables (e.g. host sex, host size), failure to identify these important confounding variables could significantly affect the ability of these methods to correctly identify PIHM. However, both of these issues – inferring process from pattern and confounding variables – are well-recognized limitations of most statistical inference and are addressed via judicious model specification and selection (Seber and Lee, 2003).

As suggested by Lester (1984), these methods for estimating PIHM can provide preliminary insight into whether or not PIHM deserves further exploration. However, we stress that these methods are an exploratory tool for assessing the role of PIHM in a system, and potential users should critically evaluate whether they think they have a large enough sample size and an appropriate host survival function/post-mortality distribution for the methods developed in this paper to be applicable. Even if they are applicable, inferring PIHM from distributional data is no substitute for field experiments and an in-depth understanding of the natural history of the host-parasite system under consideration.

Acknowledgments

We thank the Briggs Laboratory group, Kuris/Lafferty Laboratory group, Theoretical Ecology group at University of California, Santa Barbara (USA), and two anonymous reviewers for helpful feedback. MW was supported by a National Science Foundation, USA, Graduate Research Fellowship (Grant No. DGE 1144085) and the University of California Regents (USA). CB was supported by a National Institute of Health (USA) grant 1R01GM109499 from the Ecology of Infectious Disease program.

References

- Adjei, E.L., Barnes, A., Lester, R.J.G., 1986. A method for estimating possible parasite-related host mortality, illustrated using data from *Callitetrarhynchus gracilis* (Cestoda: Trypanorhyncha) in lizardfish (*Saurida* spp.). *Parasitology*. 92, 227 – 243.
- Anderson, R.M., Gordon, D.M., 1982. Processes influencing the distribution of parasite numbers within host populations with special emphasis on parasite-induced host mortalities. *Parasitology*. 85, 373 – 398.
- Anderson, R.M., May, R.M., 1978. Regulation and stability of host-parasite interactions: I. Regulatory processes. *J. Anim. Ecol.* 47, 219 – 247.
- Barbour, A.D., Pugliese, A., 2000. On the variance-to-mean ratio in models of parasite distributions. *Adv. Appl. Probab.* 32, 701 – 719.
- Benesh, D.P., 2011. Intensity-dependent host mortality: what can it tell us about larval growth strategies in complex life cycle helminths? *Parasitology*. 138, 913 – 925.
- Bolker, B.M., 2008. *Ecological Models and Data in R*. Princeton University Press, Princeton, New Jersey.
- Boswell, M.T., Patil, G.P., 1970. Chance mechanisms generating the negative binomial distributions, in: Patil, G.P. (Ed.), *Random Counts in Scientific Work Vol. 1*. Pennsylvania State University Press, USA.
- Brooker, S., Bethony, J., Hotez, P.J., 2004. Human hookworm infection in the 21st century. *Adv. Parasit.* 58, 197 – 288.
- Calabrese, J.M., Brunner, J.L., Ostfeld, R.S., 2011. Partitioning the aggregation of parasites on hosts into intrinsic and extrinsic components via an extended Poisson-gamma mixture model. *PLoS One* 6, e29215.
- Collet, D., 2002. *Modelling Binary Data*. Chapman & Hall, London, UK.
- Cox, D.R., Donnelly, C.A., Bourne, F.J., Gettinby, G., McInerney, J.P., Morrison, W.I., Woodroffe, R., 2005. Simple model for tuberculosis in cattle and badgers. *Proc. Natl. Acad. Sci.-Biol.* 102, 17588 – 17593.
- Coyne, M.J., Smith, G., McAllister, F.E., 1989. Mathematic model for the population biology of rabies in raccoons

- in the mid-Atlantic states. Am. J. Vet. Res. 50, 2148 – 2154.
- Crofton, H.D., 1971. A quantitative approach to parasitism. Parasitology. 62, 179 – 193.
- De Castro, F., Bolker, B., 2005. Mechanisms of disease-induced extinction. Ecol. Lett. 8, 117 – 126.
- Dobson, A.P., Hudson, P.J., 1992. Regulation and stability of a free-living host-parasite system: *Trichostrongylus tenuis* in red grouse. II. Population models. J. Anim. Ecol. 61, 487 – 498.
- Duerr, H.P., Dietz, K., Eichner, M., 2003. On the interpretation of age–intensity profiles and dispersion patterns in parasitological surveys. Parasitology. 126, 87 – 101.
- Ferguson, J.A., Koketsu, W., Ninomiya, I., Rossignol, P.A., Jacobson, K.C., Kent, M.L., 2011. Mortality of coho salmon (*Oncorhynchus kisutch*) associated with burdens of multiple parasite species. Int. J. Parasitol. 41, 1197 – 1205.
- Isham, V., 1995. Stochastic models of host-macroparasite interaction. Ann. Appl. Probab. 5, 720 – 740.
- Johnson, P.T.J., McKenzie, V.J., 2008. Effects of Environmental Change on Helminth Infections in Amphibians: Exploring the Emergence of *Ribeiroia* and *Echinostoma* Infections in North America., in: Fried, B., Toledo, R. (Eds.), The Biology of Echinostomes: From the Molecule to the Community. Springer, New York, USA, pp. 249 – 280.
- Joly, D.O., Messier, F., 2004. The distribution of *Echinococcus granulosus* in moose: Evidence for parasite-induced vulnerability to predation by wolves? Oecologia 140, 586 – 590.
- Kendall, D.G., 1948. On the generalized “birth-and-death” processes. Ann. Math. Stat. 19, 1 – 15.
- Kirk, R.S., 2003. The impact of *Anguillicola crassus* on European eels. Fisheries Manag. Ecol. 10, 385 – 394.
- Lanciani, C.A., Boyett, J.M., 1989. Demonstrating parasitic water mite-induced mortality in natural host populations. Parasitology, 81, 465 – 475.
- Langwig, K.E., Voyles, J., Wilber, M.Q., Frick, W.F., Murray, K.A., Bolker, B.M., Collins, J.P., Cheng, T.L., Fisher, M.C., Hoyt, J.R., Lindner, D.L., McCallum, H.I., Puschendorf, R., Rosenblum, E.B., Toothman, M.,

435 Willis, C.K., Briggs, C.J., Kilpatrick, A.M., 2015. Context-dependent conservation responses to emerging
436 wildlife diseases. *Front. Ecol. Environ.* 13, 195 – 202.

437

438 Lester, R.J.G., 1984. A review of methods for estimating mortality due to parasites in wild fish populations.
439 *Helgolander Meeresun.* 37, 53 – 64.

440

441 Lester, R.J.G., 1977. An estimate of mortality in a population of *Perca flavescens* owing to the trematode
442 *Diplostomum adamsi*. *Can. J. Zoolog.* 55, 288 – 292.

443

444 Logiudice, K., 2003. Trophically transmitted parasites and the conservation of small populations: raccoon
445 roundworm and the imperiled allegheny woodrat. *Conserv. Biol.* 17, 258 – 266.

446

447 McCallum, H., 2012. Disease and the dynamics of extinction. *Philos. T. R. Soc. B.* 367, 2828 – 2839.

448

449 McCallum, H.I., 2000. Host-pathogen and host-parasite models, in: Lawton, J.H., Likens, G.E. (Eds.), *Population*
450 *Parameters: Estimation for Ecological Models*. Blackwell Science Ltd., Oxford, UK, pp. 284 – 312.

451

452 Roeber, F., Jex, A.R., Gasser, R.B., 2013. Impact of gastrointestinal parasitic nematodes of sheep, and the role of
453 advanced molecular tools for exploring epidemiology and drug resistance - an Australian perspective.
454 *Parasites Vectors* 6, 153.

455

456 Rousset, F., Thomas, F., Meeûs, T.D., Renaud, F., 1996. Inference of parasite-induced host mortality from
457 distributions of parasite loads. *Ecology* 77, 2203 – 2211.

458

459 Royce, L.A., Rossignol, P., 1990. Epidemiology of honey bee parasites. *Parasitol. Today.* 6, 348 – 353.

460

461 Schotthoefer, A.M., Cole, R.A., Beasley, V.R., 2003. Relationship of tadpole stage to location of echinostome
462 cercariae encystment and the consequences for tadpole survival. *J. Parasitol.* 89, 475 – 482.

463

464 Seber, G.A.F., Lee, A.J., 2003. *Linear Regression Analysis*. John Wiley; Sons, Inc, Hoboken, New Jersey, USA.

465

466 Shaw, D.J., Dobson, A.P., 1995. Patterns of macroparasite abundance and aggregation in wildlife populations: a
467 quantitative review. *Parasitology.* 111, 111 – 133.

468

469 Shaw, D.J., Grenfell, B.T., Dobson, A.P., 1998. Patterns of macroparasite aggregation in wildlife host populations.

470 Parasitology. 117, 597 – 610.

471

472 Tillé, A., Lefèvre, C., Pastoret, P.P., Thiry, E., 1991. A mathematical model of rinderpest infection in cattle
 473 populations. *Epidemiol. Infect.* 107, 441 – 452.

474

475 Tompkins, D.M., Dobson, A.P., Arneberg, P., Begon, M., Cattadori, I.M., Greenman, J.V., Heesterbeek, J.A.P.,
 476 Hudson, P.J., Newborn, D., Pugliese, A., Rizzoli, A.P., Rosa, R., Rosso, F., Wilson, K., 2002. Parasites and
 477 host population dynamics, in: Hudson, P.J., Rizzoli, A., Grenfell, B.T., Heesterbeek, H., Dobson, A.P.
 478 (Eds.), *The Ecology of Wildlife Diseases*. Oxford University Press, Oxford, UK, pp. 45 – 62.

479

480 Walther, B.A., Moore, J.L., 2005. The concepts of bias, precision and accuracy, and their use in testing the
 481 performance of species richness estimators, with a literature review of estimator performance. *Ecography*.
 482 28, 815 – 829.

483

484 Wilson, K., Bjoernstad, O.N., Dobson, A.P., Merler, S., Poglayen, G., Read, A.F., Skorpington, A., 2002.
 485 Heterogeneities in macroparasite infections: patterns and processes, in: Hudson, P.J., Rizzoli, A., Grenfell,
 486 B., Heesterbeek, H., Dobson, A. (Eds.), *The Ecology of Wildlife Diseases*. Oxford University Press,
 487 Oxford, UK, pp. 6 – 44.

488

Figure Legends

Fig. 1. A schematic representation of the iterative approach of the Crofton Method. (A) The light gray shows the pre-mortality distribution that the Crofton Method is trying to estimate from the dark grey post-mortality distribution. The Crofton Method proceeds by truncating the post-mortality data at different levels (t_i , e.g. $i = 0, \dots, 5$) and finding the pre-mortality host population size (N_p), pre-mortality mean parasite intensity (μ_p), and pre-mortality parasite aggregation (k_p) that best fit the truncated data. (B) The parameter N_p is then plotted against the truncation level t_i to determine if a “kink” occurs in the parameter values (Lester, 1984). This “kink” indicates that parasite-induced host mortality (PIHM) is occurring in the system. In the given example, PIHM is occurring in the system as visualized by the distinct “kink” at t_4 .

Fig. 2. The simulation results comparing the power and the Type I error of the Adjei Method and the Likelihood Method across a range of different sample sizes. (A) Five potential shapes for host-survival functions are shown. In the simulations we used a gradual survival function (dotted line), a moderate survival function (dashed line), and a steep survival function (solid line). The linear and immediate survival functions represent two potential extremes that we do not include in the simulations. For each of these survival functions and various parameter combinations, we tested the Type I error and power of the Likelihood (Like.) Method and Adjei Method. (B) The simulation gives the Type I error of each method over a range of pre-mortality sample sizes with a pre-mortality mean parasite intensity (μ_p) of 50 and pre-mortality parasite aggregation (k_p) at 0.5. The thin, dashed grey line shows the pre-set significance level of 0.05. (C) The simulation gives the power of each method for detecting parasite-induced host mortality (PIHM) over a range of post-mortality sample sizes for $\mu_p = 50$ and $k_p = 0.5$. In general, the Likelihood Method has higher power and lower Type I error than the Adjei Method. (See Supplementary Figs. S1 - S3 for Type I error and power results for all parameter combinations.)

Fig. 3. The power of the Likelihood Method (Like.) to detect parasite-induced host mortality (PIHM) for gradual, moderate and steep host survival functions when the parameters pre-mortality mean parasite intensity (μ_p), pre-mortality parasite aggregation (k_p), a of the host survival function, and b of the host survival function were jointly estimated. The curves were generated from 500 simulations for 10 pre-mortality sample sizes, N_p . The vertical lines indicate the sample size at which the power for the Likelihood Method with steep and moderate survival functions is 0.8 (75 hosts for steep functions and 408 for moderate functions). The Likelihood Method with a gradual survival function never has a power above 0.8.

Fig. 4. Bias (absolute value of the standardized bias) and precision (coefficient of variation) for the Likelihood Method (Like.) and Adjei Method estimates of the a parameter of the host survival function and the LD_{50} of the host survival function based on simulated parasite-induced host mortality (PIHM) data over a range of post-mortality sample sizes. As the coefficient of variation increases, precision decreases. The pre-mortality parameters for this simulation were pre-mortality mean parasite intensity (μ_p) equal to 50 and pre-mortality parasite aggregation (k_p) equal to 0.5. The figure shows the simulations for three different host survival functions (gradual, moderate and steep), each with the same LD_{50} . Bias and precision results of LD_{50} and a for all other parameter combinations can be found in Supplementary Figs. S4 - S9.

Table 1. Comparison of the parasite-induced host mortality (PIHM) predictions of previously used host-parasite datasets from Crofton (1971) and Adjei et al. (1986) with those given by the Adjei Method and the Likelihood Method. The first column specifies the identity of the dataset, the second column specifies whether or not the authors indicated that PIHM was occurring in the system based on a qualitative assessment, the third column indicates whether or not the Likelihood Method with pre-mortality parameters estimated from the Crofton Method detects significant PIHM, and the final column indicates whether the Adjei Method with pre-mortality parameters estimated from the Crofton Method detects PIHM. If a method detected significant PIHM the predicted LD_{50} is given in parentheses.

Data Set (sample size)	Author detected PIHM	Likelihood Method	Adjei Method
Crofton, Station 1 ($n= 538$)	Yes	Yes (7.27)	Yes (9.33)
Crofton, Station 2 ($n= 507$)	Yes	Yes (6.92)	Yes (14.95)
Crofton, Station 3 ($n= 633$)	Yes	Yes (5.93)	Yes (5.98)
Crofton, Station 4 ($n= 486$)	No	No	Yes (7.99)
Crofton, Station 5 ($n= 276$)	No	No	Yes (10.58)
Crofton, Station 6 ($n= 191$)	No	No	No
Adjei et al., <i>Saurida tumbil</i> female ($n= 446$)	Yes (5.7)	No	Yes (6.37)
Adjei, <i>S. tumbil</i> male ($n= 452$)	Yes (3.4)	Yes (3.42)	Yes (3.66)
Adjei et al., <i>Saurida</i> <i>undosquamis</i> female ($n= 2573$)	Yes (3.2)	Yes (3.04)	Yes (3.11)
Adjei et al., <i>S. undosquamis</i> male ($n= 2440$)	Yes (1.8)	Yes (1.83)	Yes (1.78)

Figure 1

Figure 2

Figure 3