Fisheries Research 197 (2018) 45–49

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres

Research paper

Nonparametric tests of double-tagging assumptions

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ARTICLE INFO

Handled by George A. Rose

Keywords:
Bayesian methods
Fisher's Exact Test
Monte Carlo simulation
Nonparametric statistics
Tag dependence
Tag shedding

ABSTRACT

Shedding rates of tags on fish are commonly estimated from double-tagging experiments, for which an assumption of independence between the two tags on a fish is required. For tags of qualitatively different types, a nonparametric test for this assumption was proposed by Myhre (1966), making use of concurrent double- and single-tagging of fish. We extend Myhre's test by developing a nonparametric Bayesian test that is also applicable to the common situation where the two tags attached to a fish are identical and assumed to shed at the same rate; the validity of this assumption can be checked by an extra test that we supply in the case that each tag is identified uniquely. In addition to dependence between tags, the dependence test can also be triggered by departures from other experimental assumptions, such as marked variation in the expertise of taggers. We recommend the dependence test for monitoring tag-return data on an ongoing basis during an experiment. We apply our test to Atlantic cod tagging data listed by Barrowman and Myers (1996). Frequentist tests based on Fisher's Exact Test are also presented.

1. Introduction

Wild fish are often tagged to allow estimation of mortality rates or population sizes (see review in Pine et al., 2003). However, individual fish that lose all their tags are seldom detected after recapture, which leads to biases in the mortality rate estimates. In response, shedding rates are mainly estimated from double-tagging experiments, for which an assumption of independence with respect to tag-shedding between the tags on individual fish is needed. Models for estimating shedding rates from double-tagging experiments using conditional likelihoods, i.e., without the need to estimate mortality rates or the fraction of fish caught, have been developed by Gulland (1961), Chapman et al. (1965), Bayliff and Mobrand (1972) and Kirkwood (1981), amongst others.

If tags on the same fish exhibit dependence with respect to tag shedding, linking or merging the above models with models that estimate mortality rates and population size may lead to seriously erroneous estimates of these population parameters. Beverton and Holt (1957, ch. 14) discuss the possibility that shedding of a tag may depend on whether the other tag attached to the same fish is still attached. For example, an infection may begin at one tag site and spread to the other, so both tags shed at similar times; or an animal may try hard to remove a tag, and if successful will know how to quickly remove the other tag. Some events may remove all tags at once from a fish. Other authors have proposed that there could be dependence between tags with respect to deaths due to tagging; e.g., Myhre (1966), Barrowman and Myers (1996) and Hampton (1997) noted that attaching two tags might be more harmful to a fish than attaching only one tag. Hampton (1997) and Cadigan and Brattey (2006) considered dependence between tags with respect to the reporting rate, in that two tags on a recaptured fish might be more frequently noticed than one tag. Also the financial incentive to return two tags is higher than for one tag, as the reward for returning two tags is double that for returning one tag.

Studies that include auxiliary information have shown that the independence assumption often fails (see details below), and some authors (e.g., Barrowman and Myers, 1996; Diefenbach and Alt, 1998; Hearn et al., 1991; Shaughnessy, 1994) have proposed methods to deal with dependence between tags on the same animal. Ideally, every double-tagging study should be designed to allow statistical assessment of the independence assumption, although it is also important that the proportion of double-tagged fish be kept high to maximize the number of reported recoveries and facilitate precise estimation of population parameters.

When dependence is detected, it is commonly dealt with by allowing different parameter values for the shedding risks before and after any tags have been shed. This has been employed by Barrowman and Myers (1996, Appendix) for Northwest Atlantic cod *Gadus morhua*, Diefenbach and Alt (1998) for black bears *Ursus americanus*, Rivalan

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http://dx.doi.org/10.1016/j.fishres.2017.09.015
Received 24 May 2017; Received in revised form 15 September 2017; Accepted 16 September 2017

et al. (2005) for leatherback turtles *Dermochelys coriacea*, McMahon and White (2009) for southern elephant seals *Mirounga leonina*, and Laake et al. (2014) for black bears. Direct evidence of dependence mechanisms is provided by Siniff and Ralls (1991) who observed some Californian sea otters *Enhydra lutris* biting off their tags, presumably both in quick succession, while others ignored their tags, and Bradshaw et al. (2000) who found higher rates of tag shedding by New Zealand fur seal *Arctocephalus forsteri* pups whose nursery sites were rocky, implying that some pups would quickly lose both their tags by snagging against rocks, while those in non-rocky nursery sites were likely to retain both their tags. Hearn et al. (1991) found dependence caused by variation in the skills of tagging operators, which they dealt with by fitting a separate set of parameter values to each operator (see also Chambers et al., 2015; Shaughnessy, 1994).

Other studies concentrate on reporting rates. Myhre (1966) assumes that dependence is due to a higher reporting rate for double-tagged fish and describes estimation of the ratio. Barrowman and Myers (1996, Section 5) describe a model for different types of tag in which one type has 100% visibility and the other on its own has some lower rate: the resulting parameter estimates could be included in mortality models.

The standard double-tagging field experiment without auxiliary information allows evaluation of the tag-independence assumption only in extreme cases where the proportion of single-tag returns decreases over some time interval and tags therefore appear to spontaneously reattach themselves to fish (Hearn et al., 1991). Myhre (1966), however, proposed an experimental design that included a concurrent single-tagging experiment and derived a nonparametric statistical test for dependence. A "nonparametric" test is one that does not require the tag shedding rate to be a parametric function of time at liberty: such a test allows assessment of the data before fitting any complex mathematical model.

Myhre's test can also detect non-compliance with experimental protocols, such as non-uniformity in tagging or recovery practices as described above, or the extra potential problem that some fishers may believe that it is sufficient for them to return only one tag and either retain the second tag as a souvenir or return the fish to water with the second tag still attached.

We extend Myhre's test by deriving a nonparametric test for tag dependence when the two tags on a double-tagged fish are completely interchangeable and assumed to have the same shedding rate. Our test can also be triggered by failure of the assumption that the two tags are governed by the same shedding rate. If each tag is identified uniquely, the equal-shedding-rate assumption can be tested separately and we supply a suitable testing method.

We apply our test to data from Atlantic cod tagged during 1979 in the Northwest Atlantic and analyzed by Barrowman and Myers (1996).

2. Tags of different types: existing theory

2.1. Single- and double-tagging

To allow comparability between single- and double-tagging, the ideal experimental design requires that the different categories of tagged fish be released on a "rotation basis" (Myhre, 1966). For example, the first fish may be tagged with an A tag, the next with an A and a B tag, and the following fish with a B tag, with this pattern repeated until the target numbers are reached. The A and B tags may be different tag types: a Petersen disc tag and a spaghetti tag were used in the experiment analyzed by Barrowman and Myers (1996). Alternatively, they could be of the same type, but fall into different categories: for example, information may have been recorded about the attachment position for each tag on a fish. One position may be more difficult for the tagger to reach, or may have a higher shedding rate even when tags are correctly attached.

Suppose N^{AB} fish are double-tagged with an A and a B tag, N^A fish with a single A tag and N^B fish with a single B tag, and that r^{AB}_{AB}, r^{AB}_{A} and r^{AB}_{B} fish are recovered and reported from the double-tagged fish, and r^A_A and r^B_B fish are recovered and reported from the single-tagged fish: superscripts indicate tag types upon release and subscripts tag types upon recapture. The rotation basis on which tagging is conducted (see above) ensures that the time periods over which recoveries are made will be the same for the two tag types and for single- and double-tagged fish. The number of fish that have lost both their tags is usually not observable. We also use the subscript "+" to denote that a recovered fish may or may not retain its tag of the other type: e.g., the number of fish originally double-tagged that are recovered with an A tag is $r^{AB}_{A+} = r^{AB}_{AB} + r^{AB}_{A}$.

If the shedding of A tags is independent of the presence or absence of B tags, the expected proportion of A tags reported for all or part of the experiment is the same for both release subsets, AB and A (Myhre, 1966), i.e.,

$$E(r^{AB}_{A+})/N^{AB} = E(r^A_A)/N^A. \tag{1}$$

Similarly, if the shedding of B tags is independent of the presence of A tags,

$$E(r^{AB}_{B+})/N^{AB} = E(r^B_B)/N^B. \tag{2}$$

The equality of these ratios can readily be tested using the Pearson chi-square test (Myhre, 1966, pp. 12–13).

We note that this test can also be conducted by Fisher's Exact Test (Fisher, 1935a,b) (see description in Dickinson Gibbons, 2004). We will present results from both the Bayesian tests that we describe below and from Fisher's Exact Test and related tests. We prefer the Bayesian tests because we believe them to be more logical and in some cases more powerful than the equivalent tests based on Fisher's Exact Test.

2.2. Bayesian version

The test of Eqs. (1) and (2) has a Bayesian version (Good, 1957; Lindley, 1964) which, given a computer and statistical software, is easy to apply and very accurate for any sample size; other common tests such as the chi-square test are accurate only for large sample size. Taking (1) as an example, the number of recaptures $r = r^{AB}_{A+}$ or r^A_A follows a binomial distribution with parameters N and p, where $N{=}N^{AB}$ or N^A respectively, and $p = p^{AB}_{A+}$ or p^A_A is the probability that a fish tagged at the beginning of the experiment is later recovered with an A tag (with or without an accompanying B tag) and reported. The Bayesian test treats p as a random variable, specifying some prior distribution in the absence of any data and then combining this with the data to derive a posterior distribution. Monte Carlo simulation of the posterior distributions of p^{AB}_{A+} and p^A_A can be used to test the null hypothesis that p^{AB}_{A+} does not differ consistently from p^A_A.

For the prior distribution, Good (1957) proposed the beta distribution, which is the conjugate prior for the binomial distribution (Raiffa and Schlaifer, 1961; G. A. Barnard in Wetherill, 1961). The beta distribution, denoted $\mathrm{B}(\alpha, \beta)$, has the probability density

$$f(p;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)} p^{\alpha-1}(1-p)^{\beta-1}$$

over the range $0 < p <$, where α and β are the parameters of the distribution. If the prior distribution is beta with parameter values α_0 and β_0, the posterior is also beta with parameter values $\alpha = \alpha_0 + r$ and $\beta = \beta_0 + N - r$. If there is no prior information about recovery rates, the parameters α_0 and β_0 can both be set to zero, yielding an improper prior which does not take finite positive values anywhere in the interval $0 < p < 1$ but still yields sensible posterior distributions. Then the posterior distributions are

$$p^{AB}_{A+} \sim \mathrm{B}(r^{AB}_{A+},\ N^{AB} - r^{AB}_{A+}) \tag{3}$$

and

$$p^A_A \sim \mathrm{B}(r^A_A,\ N^A - r^A_A)\ . \tag{4}$$