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Frailty models for the estimation of tag shedding rates with tagger effects

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ABSTRACT

Double tagging studies are used to estimate the proportion of originally tagged fish that shed their tags prior to recapture, but models typically fitted to double tag recoveries have been subject to restrictive assumptions. For example, a common assumption is that the shedding rates of all tags are identical. Hearn et al. (Hearn, W.S., Leigh, G.M., Beverton, R.J.H., 1991. ICES J. Mar. Sci. 48, 41–51) found differences in shedding rates between taggers, and demonstrated algebraically that such differences lead to biases in estimators of shedding rates. However, widely applicable models that account for differences in shedding rates between taggers have not been developed. We adapt the proportional hazards model to the problem of estimating tag shedding rates from double-tag recovery data. Differences in shedding rates between taggers are modelled using multiplicative random effects or frailties. The frailty models are fitted to recoveries from a 1990s tagging study of southern bluefin tuna (*Thunnus maccoyii*) at exact times-at-liberty and the results compared with models previously applied for this species.

1. Introduction

The shedding of tags by fish can bias tag-based estimators of harvest rates and survival rates unless the tag shedding is properly accounted for (Arnason and Mills, 1981). Double tagging studies, first described by Beverton and Holt (1957), are used to provide information on the rate that tags are shed by fish. Given certain assumptions, tag shedding rates can be inferred from models fitted to observed recoveries of double-tagged fish that retain one and two tags given their times-at-liberty. Beverton and Holt (1957) supposed a proportion of tags might be shed immediately after tagging when the fish are released (type-1 shedding) and the remainder would be susceptible to shedding later at random at some steady rate (type-2 shedding).

The earliest tag shedding models assumed all tags were subject to the same shedding rates and that instantaneous type-2 shedding rates did not vary with time-at-liberty. Models of this type continue to be popular. However, Kirkwood (1981) observed that tag shedding models that assumed a common, time-invariant, tag shedding rate for all tags sometimes appeared to overestimate the proportion of tags shed by southern bluefin tuna (SBT) after extended times-at-liberty. He proposed models assuming that the shedding rates of individual tags were gamma distributed random variables. The models described by Kirkwood (1981) have since been found to sometimes, but not always, provide a better fit to double tag recoveries of SBT (e.g., Hampton and Kirkwood, 1990) and other fish species (e.g., Cadigan and Brattey, 2003) than models assuming all tags have the same shedding rate.

Whilst the models described by Kirkwood (1981) account for a proportion of overall variability in tag shedding rates, the heterogeneity modelled is assumed completely random. No dependence in tag shedding rates between tags is considered. The consequences of dependencies in tag shedding rates between the two tags attached to each fish caused by using taggers with different skill levels are examined by Hearn et al. (1991). They showed algebraically that standard estimators of overall shedding rates are negatively biased when fitted to recoveries pooled from two taggers with different shedding rates. The bias becomes larger as the true proportion of tags shed increases. They also investigated likely differences in shedding rates between taggers using recoveries from double-tagging studies of SBT run during the 1960s, 1970s and 1980s.

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Table 1
Posterior means of key model parameters given to two significant figures. Numbers in parentheses are posterior standard deviations given to two significant figures.

Model	λ (year^{-1})	β	ϕ	w	ΔDIC	Posterior p
H1	0.060 (0.0022)	–	–	–	153	0.01
H2	0.047 (0.0030)	–	0.028 (0.0054)	–	93	0.25
H3	0.11 (0.013)	0.20 (0.047)	–	–	96	0.49
H4	0.074 (0.0099)	0.35 (0.18)	0.015 (0.0051)	–	75	0.48
F1	0.083 (0.0095)	–	–	10 (4.7)	75	0.02
F2	0.063 (0.0078)	–	0.039 (0.0085)	10 (4.7)	13	0.29
F3	0.14 (0.023)	0.28 (0.075)	–	11 (5.3)	24	0.48
F4	0.093 (0.016)	0.57 (0.46)	0.023 (0.0079)	11 (5.0)	0	0.48

Hearn et al. (1991) estimated tagger-specific shedding rates for a few prolific taggers from early SBT tagging studies. However, they pointed out that their tagger-specific parameter estimates were sensitive to recoveries after long times-at-liberty and were subject to high variance. Indeed some of their tagger-specific parameter estimates are suggestive of instability. For example, it was estimated that only 64.8% of tags inserted by tagger A during the first experiment survived type-1 shedding, but the estimated type-2 shedding rate of tags inserted by tagger A in the same experiment was zero. By contrast it was estimated that 96.1% of tags attached by tagger A during the second experiment survived type-1 shedding, but the instantaneous type-2 shedding rate of tags inserted by tagger A in this experiment was estimated to have been 0.178 per year. The purpose of the analyses in Hearn et al. (1991) was to investigate the extent of bias rather than to develop a particular approach for modelling tagger-specific shedding rates (George Leigh, Department of Agriculture, Fisheries and Forestry, Brisbane, Australia, personal communication 2014).

Estimates of type-1 and type-2 shedding rates for eight tagging operators were calculated by Hampton (1997) in an analysis of a tagging study of tropical tunas. He fitted separate models to recoveries from each tagger, with the number of observations fitted ranging from 42 to 106 (Hampton, 1997, Table 1). The improvement in overall log likelihood that resulted from fitting tagger-specific models compared with a pooled model was not statistically significant. However, the tagger-specific parameter point estimates varied considerably. For example, the instantaneous type-2 shedding rate using recoveries pooled from all taggers was estimated to have been approximately 0.0023 per month, but, for individual taggers, the estimated rates ranged from zero to 0.018 per month, almost eight times the combined estimate. There were simply insufficient recoveries from this study to fit separate tag shedding models for each tagger, particularly since these data comprise recoveries of tags from three different tuna species.

Polacheck et al. (2006, Appendix 14) analyzed recoveries from a 1990s double tagging study of SBT. Based on a preliminary analysis of the data they identified six groups of taggers such that the members of each group appeared to have similar shedding rates whilst shedding rates differed between groups. Separate tag shedding models were then fitted to each group. Grouping taggers in this way might be regarded as a pragmatic approach, but it can only be considered a partial solution because it fails to account for differences in shedding rates between taggers within each group. The number of groups and membership of each group is also somewhat arbitrary and the approach could be criticized for double use of the data.

A 'fixed effects' type approach to estimating tagger-specific shedding rates is suggested by Xiao (1996). However, whilst Xiao (1996) estimates the effects of sex and different tag types, his analysis of school shark (*Galeorhinus galeus*) double-tag recoveries does not include tagger effects. The problem with the approaches to modelling tagger effects proposed by Xiao (1996) and others (e.g., Hampton, 1997; Hearn et al., 1991) is that they will be unreliable in the usual case where the number of recoveries from some taggers is low. Xiao et al. (1999, p. 182) note that tagging operators can affect tag shedding rates, but add that 'hundreds or even thousands' of recoveries would be required to estimate the effects of individual taggers using their 'compartmental model'.

The estimation of tag shedding rates from double-tag recovery data is a problem of the type considered within the field of survival analysis. The link between survival analysis and analyses of double-tag recovery data is readily apparent in descriptions of previous analyses of double tagging data (e.g. Wetherall, 1982). Analyses of tag shedding data seek to infer quantities related to the distribution of times that tags are shed which are analogous to the times of deaths in studies of survival. However, the observation of tag shedding in double tagging studies of commercial fisheries data differs from standard observation of times of death or failure in survival analysis in a number of respects. Firstly, the opportunity to observe the retention or nonretention of a tag occurs only at the time of recapture. In survival analysis this would be regarded as an extreme form of 'interval censoring'. Secondly, the set of tags for which observations are realized depends on the fishing and reporting characteristics of the fishing fleets which are not random and cannot be controlled. Thirdly, and perhaps most importantly, the potential to observe an instance of tag shedding requires the retention of the other tag that was attached to the same fish. Nevertheless, methods from survival analysis that can be adapted to account for the nonstandard nature of observed recoveries from double tagging studies provide alternative approaches for the estimation of tag shedding rates.

The proportional hazards model (Cox, 1972) plays a key role in modern survival analysis. It is particularly useful for making inferences about differences in survival rates between individuals or groups. Frailty models (Clayton, 1978; Vaupel et al., 1979) are a generalization of the proportional hazards model. Multiplicative random effects, often called 'frailties', are used to model heterogeneity in survival rates. The frailties can be assumed to be independent and unique to each individual (e.g. Vaupel et al., 1979), or alternatively, groups of individuals whose survival rates are thought to be similar can be assumed to share a common frailty value (e.g., Clayton and Cuzick, 1985).

Shared frailty models offer potentially improved estimation of group survival rates in applications where the number of observations from each group is not large. For example, in an application comparing the survival times of kidney transplant grafts at different hospitals, Morris and Christiansen (1995) strongly advocated a frailty model approach over fitting separate models to data from each hospital. They noted the hierarchical structure of the frailty model increases estimation accuracy. Simulation studies examining the performance of alternative models in survival analysis applications in medicine (Andersen et al., 1999) and agriculture (Duchateau and Janssen, 2008) have also demonstrated superior performance of frailty models in the estimation of group effects over a fixed effects approach.

We fit frailty models to recoveries arising from the same 1990s double tagging study of SBT considered by Polacheck et al. (2006). Dependence in tag shedding rates due to differences in tagger skill