

The design and analysis of field studies to estimate catch-and-release mortality

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Abstract The practice of catch and release (CR) as a fisheries management tool to reduce fishing mortality is widely applied in both freshwater and marine fisheries, whether from shifts in angler attitudes related to harvest or from the increasing use of harvest restrictions such as closed seasons or length limits. This approach assumes that for CR fishing policies to benefit the stock, CR will result in much lower mortality than would otherwise occur. There are many challenges in the design of CR studies to assess mortality, and in many practical settings it is difficult to obtain accurate and precise estimates. The focus of this article is on the design and quantitative aspects of estimating CR mortality, the need for a comprehensive approach that explicitly states all components of CR mortality, and the assumptions behind these methods. A general conceptual model for CR mortality that is applicable to containment and tagging-based studies with a slight modification is presented. This article reviews the design and analysis of containment and tagging studies to estimate CR mortality over both the short and long term and then compares these two approaches. Additionally, the potential population-level impacts of CR mortality are discussed. A recurring theme is the difficulty of designing studies to estimate CR mortality comprehensively and the need for additional research into both statistical model development and field study design.

KEYWORDS: cage studies, catch and release mortality, hooking mortality, tagging studies, telemetry studies.

Introduction

Catch-and-release (CR) regulations in recreational fisheries have evolved over the last 20 years into a key tool used by management agencies to reduce fishing mortality and help rebuild depleted stocks of both marine and freshwater sportfish species (Muoneke & Childress 1994; Wilde 1998; Lucy & Studholme 2002). However, the success of this approach is predicated on the assumption that mortality caused by the CR process is minimal. The impacts of post-release mortality on overall stock size and age structure are potentially large and clearly must be considered in stock assessments and regulation planning. CR mortality is not just a concern in fisheries where angler attitudes have shifted away from consumption, but it is also a major issue related to the effectiveness of minimum size regulations and seasonal closures as a management tool for all fish

stocks. Nelson (2002) described a common scenario in recreational fisheries for the common snook, *Centropomus undecimalis* Bloch, where highly restrictive seasonal closures and bag and size regulations were implemented to reduce fishing mortality. These regulations forced Florida recreational anglers to adopt CR fishing for much of the year. The high and increasing angling effort, combined with the estimated 3% post-release mortality, led to non-harvest mortality resulting from CR fishing accounting for approximately one-third of all fishing mortality for this species.

This article explores the quantitative aspects of estimating CR mortality and suggests the need for a comprehensive approach that explicitly states the key components of CR mortality and the assumptions behind methods used to estimate each component. To focus estimation methods, CR mortality is divided into immediate mortality, short-term (~24–72 h) CR mortality and long-term (> 72 h) CR mortality. In

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addition, each of these types of mortality has other elements that are specific to each fishery that must be considered when designing a study to estimate CR mortality, such as handling mortality, hook type or depth at capture.

Immediate mortality

Immediate mortality is defined as mortality caused by acute injuries or predation resulting from the fish being hooked. This type of mortality is most often measured when a fish is dead when landed; for example Pepperell & Davis (1999) observed a black marlin *Makaira indica* (Cuvier) killed by a shark while they were tagging the marlin as part of a telemetry study.

Short-term mortality

Short-term (~24–72 h) CR mortality can be divided into two components: the first is the mortality resulting from a hooking or handling injury, and the second is the additional mortality due to indirect effects including increased predation risk following release. Predation risk following release can be high because releases often occur in risky habitats, (e.g. releases at the water surface from boat or shore) and released fish may have reduced ability to avoid predators because of injury or exhaustion (Burns & Restrepo 2002). Short-term mortality is often measured in cage or containment studies (Payer, Pierce & Pereira 1989; and multiple examples in Lucy & Studholme 2002). However, cage studies prevent the indirect mortality effects mentioned above, which may lead to underestimates of the true hooking mortality rate. Further complicating the use of cage studies are recent findings demonstrating how simply restraining animals in cages could have lethal or sublethal effects. Udomkusonsri & Noga (2005) documented the rapid development of acute ulceration response (AUR) immediately following containment in a variety of warmwater fish species. Fish suffering from AUR were susceptible to often-lethal (>87% in laboratory trials) secondary microbial infections. Telemetry is an alternative approach to estimate short-term mortality.

Long-term mortality

Long-term (>72 h) CR mortality is difficult to estimate and is often assumed to be near zero. However, this assumption requires validation. For example, injuries from barotrauma could lead to decreased feeding abilities due to damaged eyes, mouth or stomach that could cause mortality at a later time.

To assess long-term mortality, modifications of tag-return (Brownie, Anderson, Burnham & Robson 1985; Hoenig, Barrowman, Hearn & Pollock 1998a; Hoenig, Barrowman, Pollock, Brooks, Hearn & Polacheck 1998b) or telemetry survival methodology (Pollock, Winterstein, Bunck & Curtis 1989; Hightower, Jackson & Pollock 2001) likely are most appropriate. These methods require crucial model assumptions that must be carefully examined when planning a hooking mortality study. Long-term tagging studies are often performed to estimate fishing mortality rates, and it is possible to incorporate estimates of long-term hooking mortality into these existing studies, particularly if exploitation rates are high and reporting rates can be reliably estimated (see below).

A conceptual model for catch-and-release mortality

Basic model with control fish

The simplest (and ideal) situation to estimate CR mortality is where there are both 'control' and 'treatment' fish. Treatment fish are those that have been caught and released. The control fish are assumed to be identical to the treatment fish except that they have not been subject to the CR fishing process. All fish will be monitored for one time period. An instantaneous-rates mortality model can be used for both groups assuming additivity of the mortality components. The total mortality (M) for the control fish (C) at time T (M_{CT}) is defined as:

$$M_{CT} = M_{HA} + M_{CC} \quad (1)$$

and the CR total mortality (M_{HT}) is defined as

$$M_{HT} = M_{HA} + M_{HO}, \quad (2)$$

where M_{HA} is the handling mortality (from being placed in a cage or from being tagged) for control and caught-and-released fish, M_{CC} is the extra mortality resulting from capture of the control fish and M_{HO} is the mortality due to the fish being caught and released.

The goal is to estimate M_{HO} (the extra mortality resulting from CR) in an unbiased manner. Note that the finite survival rate of CR fish is

$$S_{HT} = e^{(-M_{HT})} = e^{(-M_{HA} - M_{HO})}, \quad (3)$$

and that one cannot obtain M_{HO} from hooked fish alone unless one assumes that there is no handling mortality. This is most likely not reasonable in almost all field situations and, thus, control fish are needed. The finite survival rate of control fish is

$$S_{CT} = e^{(-M_{CT})} = e^{(-M_{HA}-M_{CC})}, \quad (4)$$

therefore, the ratio of the two finite survival rates gives

$$\frac{S_{HT}}{S_{CT}} = e^{(-M_{HO}-M_{CC})} = e^{(-M_{HO})} \quad (5)$$

provided that $M_{CC} = 0$ and M_{HA} is the same for both control and CR fish.

One CR mortality estimate commonly used is based on the ratio of control and caught-and-released fish survival estimates. The finite CR mortality rate estimate is

$$\hat{M}_{HOF} = 1 - e^{(-\hat{M}_{HO})} = 1 - \left\{ \frac{\hat{S}_{HT}}{\hat{S}_{CT}} \right\}, \quad (6)$$

and the instantaneous rate version is

$$\hat{M}_{HO} = -\log_e \left(\frac{\hat{S}_{HT}}{\hat{S}_{CT}} \right). \quad (7)$$

These estimates rely on two key assumptions. First, $M_{CC} = 0$, that is there is no mortality resulting from catching the control fish. It is very difficult to find a true control in this setting. Second, M_{HA} is the same for both control and CR fish. This is probably a reasonable assumption in most applications, although it is possible that handling mortality may be different for controls and CR fish.

The standard errors of CR mortality estimates are based on the delta method (Seber 1982, p. 7). The finite CR mortality rate estimate has variance

$$\text{var}(\hat{M}_{HOF}) = \left\{ \frac{\hat{S}_{HT}}{\hat{S}_{CT}} \right\}^2 \left\{ \frac{\text{var}(\hat{S}_{HT})}{\hat{S}_{HT}^2} + \frac{\text{var}(\hat{S}_{CT})}{\hat{S}_{CT}^2} \right\}. \quad (8)$$

The instantaneous rate estimate has variance

$$\text{var}(\hat{M}_{HO}) = \frac{\text{var}(\hat{M}_{HOF})}{(1 - \hat{M}_{HOF})^2}. \quad (9)$$

The standard errors are the square root of the variance estimates.

Basic model without control fish

For both cage and tagging studies to assess CR mortality, there is a common and crucial design difficulty related to finding true controls. It is difficult to find adequate control fish for CR studies, because controls have to be available through some method of capture that has no mortality associated with it ($M_{cc} = 0$). When control fish are used, the source of the controls is commonly fish caught with some gear

other than with a hook (e.g. seine). Another alternative is to use hatchery-reared fish as controls, but this may be unreasonable as hatchery-fish behaviour and hardiness, after being reared in a controlled environment, may be quite different from that of wild fish. With any type of true control fish, their capture mortality is assumed to be 0. In the absence of true controls, the biased estimator of CR mortality is

$$\hat{M}_{HOF}^* = 1 - \hat{S}_{HT}, \quad (10)$$

only based on the CR fish (Wilde 2002). The bias is 0 only if there is no handling mortality. This estimator has variance

$$\text{var}(\hat{M}_{HOF}^*) = \text{var}(\hat{S}_{HT}). \quad (11)$$

The instantaneous rate estimate is:

$$\hat{M}_{HO}^* = -\log_e(\hat{S}_{HT}), \quad (12)$$

with variance the same as in Eqn (9).

Model to compute relative survival rates (and relative catch-and-release mortality estimates) for different groups of fish

Due to the difficulties in obtaining true control fish discussed in the previous section, a generalised model that can be used to compare the relative survival rates of different groups of fish is presented below. Common examples of groups include fish caught using different captures methods, different capture depths, fish hooked with different types of hooks or fish hooked in different locations. For simplicity, the model for two groups is presented, although more are possible. Using similar notation and assuming that the handling mortality is the same for the two groups, the survival rates for group 1 and group 2 are

$$S_{HT1} = e^{(-M_{HT1})} = e^{(-M_{HA}-M_{HO1})} \quad (13)$$

$$S_{HT2} = e^{(-M_{HT2})} = e^{(-M_{HA}-M_{HO2})}, \quad (14)$$

and the relative survival rate of the two groups is

$$\frac{S_{HT1}}{S_{HT2}} = e^{(-M_{HT1}-M_{HT2})} = e^{(-M_{HO1}-M_{HO2})} = e^{(-M_{HO12})}. \quad (15)$$

Here M_{HO1} is the instantaneous rate of hooking mortality for group 1, and M_{HO2} for group 2 with M_{HO12} the extra hooking mortality for group 1 compared with group 2. The handling mortality cancels out if the handling mortality M_{HA} is the same for both groups. Therefore, an estimate of the finite rate is:

$$\hat{M}_{HO12F} = 1 - e^{(-\hat{M}_{HO12})} = 1 - \left\{ \frac{\hat{S}_{HT1}}{\hat{S}_{HT2}} \right\}, \quad (16)$$

which is similar to Eqn (6) and has a corresponding variance to that of Eqn (8). The instantaneous rate estimate \hat{M}_{HO12} is based on the same equation as Eqn (7).

Design of containment-based catch-and-release studies

A common approach to assessing CR mortality is to capture fish using conventional angling gear and monitor their survival for short time periods (hours to days) in cages, pens, or ponds [termed 'containment studies' (Taylor, Whittington & Haymans 2001; Duffy 2002; Lucy & Arendt 2002)]. Although this approach may not always be appropriate because of the size or behaviour of the species (e.g. pelagic billfishes and tunas, Goodyear 2002), containment studies are commonly conducted for many species. An important issue in containment-study designs is the question of what is the valid experimental unit. It is unfortunately common for fisheries scientists to use, for example, one cage and view individual fish in the cage as the experimental unit. Standard results based on the binomial distribution are then used to obtain standard errors of survival rates (and hence mortality rates). If there are n fish in the cage and x survive, then using standard results we have a survival estimate of

$$\hat{S} = \frac{x}{n} \quad (17)$$

with a standard error of

$$SE(\hat{S}) = \sqrt{\frac{\hat{S}(1 - \hat{S})}{n}}. \quad (18)$$

The standard errors for CR mortality would be based on Eqn (8) or Eqn (11) and use Eqn (18) for standard error of the CR fish and the controls if controls were included; however, this measure of variation is *incorrect* as it ignores cage-to-cage effects.

Better experimental designs are either completely random or randomised block designs (Steel, Torrie & Dickey 1997) based on the replicate cages. For a completely random design, where a cage has CR or control fish only, replicate cage results based on r cages with an estimate of survival for each cage would be

$$\hat{S} = \frac{\sum_1^r \hat{S}_i}{r} \quad (19)$$

and

$$SE(\hat{S}) = \sqrt{\frac{\sum_1^r (\hat{S}_i - \hat{S})^2}{r(r-1)}}. \quad (20)$$

Here the survival estimates and standard errors apply to controls and CR fish and again the standard errors for CR mortality would be based on Eqn (8) or Eqn (11) and use Eqn (20) for standard error of the CR fish and the controls, if controls were included. These standard errors are correct in the sense that all appropriate sources of variation are included.

Another replicate cage design would be to have r cages and in each cage put both CR fish and control fish. Under this randomised block design (or paired design if there are only two groups) the CR mortality can be calculated for each cage using Eqn (6) and then calculate the mean [conceptually the same equation as Eqn (19)] and the standard error of the mean [conceptually the same equation as Eqn (20)].

A minimum sample-size example is offered to emphasise the importance of precision when designing these studies. In this example, handling mortality = 0.05 and hooking mortality = 0.10. Because no cage effects were assumed, these values are absolute minimums. With 50 control fish and 50 CR fish the estimated $SE(\hat{M}_{HOF}) = 0.059$ with a 95% confidence interval of 0–0.22. With 100 control fish and 100 CR fish the estimated $SE(\hat{M}_{HOF}) = 0.037$ with a 95% confidence interval of 0.02–0.18.

Using the same values above but with no control fish, the estimated variance is different. In this scenario the standard errors are smaller: $SE(\hat{M}_{HOF}) = 0.049$ for 50 fish and $SE(\hat{M}_{HOF}) = 0.035$ for 100 fish. This is because the ratio estimate used previously adds additional parameter variation. In this example with no controls, the approximate bias was 0.04 or 40% (0.04/the known value of 0.1) of the estimate which was due to the handling mortality being ignored.

Key points for containment-type studies are (1) use replicate cages of fish of each group (hook, bait, etc.) and (2) when possible use some sort of control group(s). If controls are not used, then relative CR rates based on comparing different groups of CR fish may be informative. Simple exercises like the example here can be quite informative in planning a CR experiment.

Design and analysis of telemetry studies

Containment studies are simple to conduct but are not possible for some species and do not allow for indirect mortality impacts, such as predation following release.

Telemetry studies offer an alternative approach to assessing CR mortality by providing detailed information on the behaviour, movement and fates of both control (if possible) and CR animals from single or multiple groups. Although telemetry studies have some limitations related to tag size, cost and effects of surgeries on animals, they should be considered for assessing short- and long-term CR mortality.

First, consider the ideal situation where there is no harvest (all fishing is CR), no emigration, 100% detection probability each sampling occasion and no tag failures. In a short-term telemetry study with two groups, the conceptual estimator for CR mortality is the same as the two-group study above [Eqn (17)]. Here it is necessary to establish *a priori* a set of rules to help determine the viability of a fish (Hightower *et al.* 2001). For example, fish present and moving are considered alive, but fish that have stopped moving for a certain period of time or have relocated to anomalous areas (such as deep, anoxic water) are considered dead. For an individual time period, survival rate is calculated as the fraction of animals still alive. This estimate would need to be generalised for multiple periods if this was used for assessment of long-term mortality.

In most field applications, animals are likely to be harvested and to emigrate, and detection probabilities are usually <100%. The use of known-fate telemetry models similar to Hightower *et al.* (2001) to estimate fishing mortality, natural mortality and relocation probability could be generalised to incorporate multiple groups. Natural and fishing mortality (or simply total mortality) could then be estimated for each group and compared.

There are practical limitations of telemetry methods for estimating CR mortality including possible effects of the tagging method (e.g. Brill, Lutcavage, Metzger, Bushnell, Arendt & Lucy 2002; Waters, Noble & Hightower 2005). Goodyear (2002) conducted a detailed simulation study evaluating the efficacy of pop-off satellite telemetry tags to track the fates of CR billfish. He demonstrated that, under perfect conditions (no tag failure, tag-induced mortality or tag loss), individual CR experiments should include a minimum of 100 tags. Given the high cost of satellite pop-off tags (US \$3000–\$5000 per tag), these experiments would have to be carefully planned. Pepperell & Davis (1999) described the vagaries of successfully monitoring the CR survival of black marlin.

There are two common limitations of many telemetry studies for assessing hooking mortality. First are the possible effects to the animal from attaching or implanting the telemetry device. To minimise surgery effects, tags are often attached externally to the fish,

which increases the chance of the tag being shed (see Pepperell & Davis 1999). There is also a trade-off between battery life and transmitter size (Bettoli, Vandergoot & Horner 2000). Very small transmitters are used to reduce tagging effects, but these small transmitters have very short battery life. Second, despite ambitious tracking efforts, monitoring the fates of pelagic species such as tunas and marlins from boats for extended periods of time is extremely difficult, given the fast, long-distance movements these animals often undertake (Pepperell & Davis 1999). New advances in telemetry tags and receivers will likely make these methods more applicable to CR studies in the near future.

Design and analysis of long-term tag-return studies

Traditional tag-and-recapture studies have been widely used in a variety of fisheries to assess the movement and mortality rates of recreationally and commercially important fishes. When adapting this approach to CR studies, ideally both control and hook-caught fish would be tagged and released. Again, because of the difficulty in obtaining controls, two or more different 'catch' treatments are usually compared. The fates of the animals from each treatment are then determined based on returns from the fishery.

A multiple-group version of the Brownie models (Brownie *et al.* 1985) can be used when tagging occurs during several time periods. This kind of data structure can be analysed in program MARK (White & Burnham 1999). It is possible to estimate the survival rates for each group in each period and also the relative survival rates between the two groups using an appropriate additive model structure. If there is only one tagging period it is only possible to estimate the relative survival rates of the two groups or, equivalently, the additional mortality in one group over another. This is equivalent to Eqn (16).

The instantaneous rate formulation of tag-return models to estimate fishing and natural mortality used by Hoenig *et al.* (1998a,b) and others could be adapted to this problem by allowing for multiple groups. Natural and fishing mortality could both be influenced by the CR process and could help identify sources of 'cryptic' mortality in managed fish populations where total mortality rates and populations may not respond to management actions designed to reduce *F* (fishing mortality) as rapidly as expected. Some generalisations are given by Jiang (2005) who considered a fishery with both harvest and CR, and where the tag was removed on capture in either case.

A common issue with tag-return studies is the low number of returns of the tagged animals to compare the different groups (e.g. hook types). A quick examination of data from the Virginia Game Fish Tagging Program (Lucy, Bain & Arendt 2002) and the NOAA Southeast Cooperative Tagging Center (Prince, Ortiz, Venizelos & Rosenthal 2002) reveals the low numbers of returns common in many tag-return programmes. For example, of the nearly 250 000 tagged animals in the Cooperative Tagging Center data base, only 4.43% of the tags have been returned. There are a variety of reasons for the low return rate, including tag loss and low reporting rates by anglers. Approaches to increasing tag retention rate often focus on angler education as poor tag placement by anglers could be a major source of tag failure. Reporting-rate estimates are notoriously difficult to determine, but are essential to reliably estimate mortality rates from tag-return studies (Hoenig *et al.* 1998a,b; Pollock, Hearn, Hoenig & Calingaert 2001).

Comparison of different types of studies

Containment vs telemetry studies

Containment studies and telemetry methods can both be used to assess short-term mortality. If both methods are feasible for the study species, then containment studies are relatively simple to design and implement, whereas a telemetry study is more complex and likely more expensive. The trade-off is that containment studies take place in an unnatural setting while telemetry studies allow the animal to be returned to the wild and provide additional information common to telemetry studies such as movement and habitat use. This is a major plus for telemetry studies; however, care must be taken to minimise the effects of the telemetry tag on animal behaviour and ultimately survival (Close, Fitzpatrick, Lorion, Li & Schreck 2003).

Telemetry vs tag-return studies

This comparison is primarily a trade-off of high-resolution data from a small number of animals (telemetry) vs likely lower resolution data from a much larger number of animals. One obvious suggestion is to try combining the two approaches (Pollock, Jiang & Hightower 2004).

Population-level impacts of CR mortality

This article has focused on the assessment of CR mortality for individual fish. The effect of CR on populations is the primary issue to anglers and fishery

managers, and assessment requires not only reliable estimates of CR mortality but also fishing effort. If the fishing effort is high, individual fish may be captured and released multiple times so that there are multiple opportunities for the fish to be subjected to this mortality risk. Under these conditions even low mortality per individual event could translate into a large impact on the population (Nelson 2002). This is a major issue, especially in many growing recreational fisheries where fishing effort remains high even with restrictive season, size and bag limits. In these situations, simulation studies have shown that the optimum fishing mortality rate could remain low even with high size limits because the unregulated F from CR mortality may not be compensated for by the size limit (L.G. Coggins, Jr, M.J. Catalano, M.S. Allen, W.E. Pine, III, unpublished data). This 'cryptic' mortality could most likely only be regulated through regulations to reduce fishing effort. In many large stock-assessments, attempts have been made to account for CR mortality (see recent stock assessments for a variety of fish stocks in the US Gulf of Mexico; <http://www.gulfcouncil.org>). However, because of limited information on the magnitude of CR mortality for most stocks, CR mortality estimates are often very poor, which increases the overall uncertainty in the stock assessment.

Conclusions and recommendations

Estimating the magnitude of CR mortality is difficult and requires careful planning and study design. For short-term containment studies, ideally, control fish should always be used. In containment-based studies, individual fish are clearly not replicates and their use as such is a form of pseudo-replication (Hurlbert 1984). When control fish are not feasible, then the estimation of the relative survival for different groups of fish (e.g. comparing two hook types) may be all that is possible. The precision of these estimates should be evaluated before an experiment takes place to help determine whether the relative survival estimates would provide adequate information to make management decisions.

Telemetry and tag-return approaches are likely the most feasible approaches for assessing the long-term effects of CR fishing. Telemetry and tag-return studies are often more complex and expensive to conduct than containment experiments but may be more realistic because containment studies limit the interactions between CR fish and the environment. Telemetry studies provide very detailed information on a small number of animals, whereas tag-return approaches provide less detail on a larger sample of animals.

Telemetry and tag-return studies are both dependent on relocation of the fish either through tag detections (telemetry) or returns from the fishery (tag-return). Uncertainty associated with the fate of animals from either a telemetry or tag-return programme must be addressed for these programmes to estimate CR mortality successfully (Hightower *et al.* 2001; Pollock *et al.* 2001).

The measurement of CR mortality and population effects has many opportunities for future research. These include more rigorous field studies to assess CR mortality, coupled with simulation and intensive field studies to assess the population level impacts of CR mortality. Estimating and understanding the population impacts of CR mortality is an exciting research area at the interface of applied statistics and fisheries management that deserves immediate attention.

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