Predicting Effort and Protected Species Bycatch Under an Effort Limit or Take Caps

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Abstract

Many production processes feature joint production of a desirable output with an undesirable byproduct. Producers and consumers of the desirable output mutually benefit at the expense of non-consumers, who bear external damage costs imposed by production of the undesirable byproduct.

A standard approach to regulating such production activities is through the combination of a limit on allowable production effort in conjunction with a cap on the level of the undesirable output. The situation is greatly complicated when the production externality is a random function which depends on the level of production effort. In this case, capping undesirable output induces a random limit on the level of the production effort, assuming further production is prohibited once the undesirable output cap is reached.

One situation which fits the above description is that of controlling protected species bycatch in commercial fisheries management. Because protected species are typically rare or endangered, and hence limited in population size and distribution, protected species bycatch is by nature a rare event, subject to random variation over time periods or areas where fishing effort occurs.

A standard approach to protected species bycatch mitigation is to employ some combination of effort limit and protected species take caps within a given fishing season, in order to ensure that fishing effort ends before an unacceptably large number of protected species takes has occurred. Given the inherent randomness of protected species bycatch for a given level of fishing effort, a number of questions of interest arise in comparing alternative bycatch management regimes, including:

1. If effort reaches the regulatory limit, what is the likely range of variation in bycatch?

2. What is the likely range of effort under regulation by protected species take caps?

3. What is the effect on the allowable range of effort if take caps are simultaneously implemented for multiple protected species?

4. With multiple take caps and an overall effort limit, what are the probabilities for hitting each of the different possible caps or limit?

A probabilistic framework is developed herein to address these and related questions. I use a Poisson distribution to model the probability distribution of bycatch conditional on a given level of effort. A Bayesian framework for deriving predictive distributions of bycatch

conditional on fishing effort is used to obtain the stochastic effort limit for a given specified limit and take caps. The methodology is applied to observer data from the Hawaii-based longline fishery for swordfish in order to address the questions posed above.

1 Marine Turtle Bycatch in the Hawaii Longline Fishery for Swordfish

The Hawaii shallow set longline fishery for swordfish has historically faced a problem with marine turtle bycatch. Of particular concern are takes (hookings) of leatherback and loggerhead turtles which are protected under the endangered species act. Since the fishery reopened in 2004 under regulations designed to reduce marine turtle interactions[1], caps of $c_1 = 17$ loggerhead turtle interactions and $c_2 = 16$ leatherback turtle interactions in addition to an effort quota of $Z_{max} = 2120$ longline sets have used to limit turtle bycatch to a level deemed to be in compliance with the Endangered Species Act and other U.S. federal conservation laws. If effort reaches either of the turtle caps or the quota during the course of the season, the fishery is closed for the balance of the year.

Based on recent evidence that sea turtle interactions have dropped substantially in the period subsequent to adopting regulations to reduce take risk, the Western Pacific Fishery Management Council (WestPac) has proposed to eliminate the effort quota entirely and to increase the respective loggerhead and leatherback take caps to $c_1 = 46$ and $c_2 = 19$. The effective impact of these proposed regulatory changes on allowable effort appears to favor an increase in allowable effort at the cost of a higher level of turtle takes. This paper proposes and demonstrates a method for quantifying the effects of such a regulatory change on allowable effort and likely turtle takes.

2 Bayesian Inference

There are at least three potential sources of stochastic variation which enter the prediction of the probability distribution of bycatch conditional on a given level of effort. One is the random nature of future

[1]Interactions refer to entanglements or hooking without regard to mortality.

protected species take experience. A second is the effect of past randomness on the estimated rate parameter. A third is the possible random variation in take risk due to changes in the factors which underly the risk. The Bayesian approach decomposes the sources of variation in the observed data into a prior distribution which summarizes the researcher's prior beliefs about values of distribution parameter(s), and a likelihood function which expresses the conditional dependence of the observations on the values of distribution parameter(s).

The key elements of the Bayesian approach are a prior distribution, generically notated $p(\theta)$, which summarizes prior beliefs about the parameter or parameters in question, and a likelihood function, represented $p(y \mid \theta)$, which may be interpreted as the probability distribution for the data y conditional on the parameter(s) θ. Estimation and inference in the Bayesian approach is based on the application of Bayes' Rule, which provides an algorithm for using the prior distribution and the observed data to obtain a posterior parameter distribution which represents updated beliefs about the parameters in light of the empirical evidence:

$$p(\theta \mid y) = \frac{p(y \mid \theta) p(\theta)}{p(y)}, \tag{1}$$

where $p(y) = \int p(y \mid \theta) p(\theta) d\theta$ is the marginal distribution of y. The data represent a given set of observations and hence may be regarded as constant in the formulation, and hence represents a scale factor which makes the posterior density integrate to 1. In light of this, Bayes' rule is often expressed in proportionality form as

$$p(\theta \mid y) \propto p(y \mid \theta) p(\theta), \tag{2}$$

with the understanding that $p(y)$ may be recovered by integration, as shown above.

2.1 Exposure Model of Protected Species Take Risk

Standard models of catch and effort assume the catch is a monotonically increasing function of fishing effort and the stock of the species in question. The challenge in modeling rare event processes such as infrequent takes of protected sea turtles is to characterize the dependence of catch on effort and the stock level in a manner which reflects the random nature of rare event counts.

To develop a model of incidental take of protected species, I assume the protected species take count y follows a Poisson process with rate parameter $Ey = \lambda$. The Poisson probability for y takes conditional on the rate parameter is

$$p(y \mid \lambda) = e^{-\lambda} \frac{\lambda^y}{y!}. \tag{3}$$

I begin with the assumption that the expected number of takes is described by the Schaeffer production function

$$\lambda = qZS = Z\theta, \tag{4}$$

where q is catchability, Z is a measure of nominal fishing effort and S is the stock of the bycatch species. This model expresses the direct dependence of the expected bycatch rate on nominal effort, the bycatch species stock and catchability. If the data are limited to fisheries-dependent catch and effort for a single fishery, it is not possible to separately identify q and S, and hence they are combined into a bycatch per unit of effort (BPUE) parameter, $\theta = Ey/Z = qS$.

2.2 Data

To implement this model of turtle catch rate empirically, I consider the available data, which includes takes of loggerhead and leatherback turtles and nominal effort (numbers of sets) over the period[2] from the second quarter of 2004 through the fourth quarter of 2007.

Since the 2004 data was only reported on an annual basis, thirteen different periods of data is available since 2004. This raises the question of whether the sample size is sufficiently large to yield statistically significant results. Viewed another way, the data represent roughly four million hooks worth of effort. Though generally not directly observed, each hook can be envisioned as a separate observation which may either come up empty, or else come up with a swordfish, a loggerhead turtle, a leatherback turtle or some other hooked species. The Bayesian inference approach used in this paper avoids the debate of whether the sample size is large enough to yield statistically

[2]The the Hawaii shallow set longline fishery reopened in May 2004 subject to 100 percent observer coverage and gear restrictions which were proven to dramatically reduce the takes of endangered sea turtles. Effort is also expressed in the observer reports in terms of the number of hooks, but a decision was made to use the number of sets to measure nominal effort, as the effort limit is expressed in number of sets.

significant results by estimating predictive distributions which implicitly take into account of the number of hooks fished, regardless of the number of aggregate observations on effort and turtle bycatch.

2.3 Estimation

The in season caps on loggerhead and leatherback takes in the Hawaii shallow set longline fishery coupled with a 100 percent observer coverage requirement pose an econometric issue of truncation: So long as all sets of fishing effort are observed and observers report truthfully, the observed numbers of loggerhead and leatherback turtle interactions will be truncated at the capped levels. To reflect this in the estimation methodology, the likelihood function must be modified to take truncation into consideration.

For the Poisson model with effort measured by the number of sets $\mathbf{Z} = (Z_1, Z_2, \ldots, Z_N)$, BPUE parameter θ, the Poisson likelihood function reflecting truncation at protected species take cap level[3] c_i is given by:

$$p(\mathbf{y} \mid Z_i, \theta) \propto \prod_{i=1}^{N} \frac{f(y_i|Z_i, \theta)}{F(c_i|Z_i, \theta)}, \tag{5}$$

where $f(y_i|Z_i, \theta) = \frac{e^{-\theta Z_i}(\theta Z_i)^{y_i}}{y_i!}$ is the Poisson probability function, $F(c_i|Z_i, \theta) = \sum_{j=0}^{c_i} f(j|Z_i, \theta)$ is the Poisson cumulative distribution function evaluated at the cap c_i and $\mathbf{y} = (y_1, y_2, \ldots, y_N)$ represents the vector of count observations across N sampling units.

The Poisson distribution represents a case where the form of the likelihood gives rise to what is known as a conjugate prior, which is a parametric probability distribution which may be used to quantify prior beliefs about the parameter in a natural manner that reflects available information before considering the observed data. The conjugate prior for the Poisson distribution is

$$p(\theta) \propto e^{-\beta\theta}\theta^{\alpha-1}, \tag{6}$$

which (with the addition of a normalizing factor) is known as the $\Gamma(\alpha, \beta)$ distribution. The distribution has mean and variance parameters given by

$$E(\theta) = \frac{\alpha}{\beta} \tag{7}$$

[3]The value of c_i can decrease over the course of the season because the take caps are cumulative. For example, if $c_1 = 17$ and two takes occurred in the first quarter, $c_2 = 17 - 2 = 15$.

and

$$Var(\theta) = \frac{\alpha}{\beta^2}, \tag{8}$$

and for suitable choice of the location parameter α and shape parameter β, the distribution can reflect a wide range of prior beliefs about the rate parameter θ.

Applying Bayes'rule with a Gamma distribution prior to the simple case of uncapped turtle bycatch yields the following posterior density:

$$p(\theta \,|\, \mathbf{y}, \mathbf{Z}) \propto e^{-(\beta + \sum_{i=1}^{N} Z_i)\theta} \theta^{\alpha + \sum_{i=1}^{N} y_i - 1}, \tag{9}$$

which is a $\Gamma\left(\alpha + \sum_{i=1}^{N} y_i - 1, \beta + \sum_{i=1}^{N} Z_i\right)$ distribution. The form of the posterior suggests that the roles of α and β are analogous to the prior number of takes and the prior number of sets, respectively.

Calculating the posterior is complicated by truncation of allowable turtle bycatch y_i in each period at the caps c_i. Given 100 percent observer coverage, I assume the caps are strictly enforced. The posterior reflecting truncation is given by Bayes' rule as

$$p(\theta \,|\, \mathbf{y}, \mathbf{Z}) \propto p(\theta \,|\, \mathbf{y}) \prod_{i=1}^{N} \frac{f(y_i | Z_i, \theta)}{F(c_i | Z_i, \theta)}, \tag{10}$$

which cannot be written in a simple form due to the product of summations in the denominator. This poses no unsurmountable computational obstacle, as the posterior may be evaluated numerically over a closely-spaced grid of values of θ to obtain an arbitrarily close approximation to the exact posterior.

The simplifying assumption is made for this paper that

$$p(\theta) \propto 1, \tag{11}$$

which can be interpreted as an improper gamma prior with $\alpha = 1$ and $\beta = 0$. This function is not itself integrable, but results in an integrable posterior density after multiplying by the likelihood. The fact that α and β do not explicitly appear in the posterior may help deflect criticism that the posterior depends strongly on prior assumptions.

2.4 The Effort Survival Function

The prediction of allowable fishing effort and turtle bycatch is complicated in the case of regulation by turtle caps and an effort limit by feedback from the risk of hitting a turtle cap before the effort limit is reached. For example, though the aggregate in-season effort limit in the Hawaii shallow set longline fishery was $Z_{max} = 2120$, the fishery was closed in March 2006 due to hitting the loggerhead turtle take cap of 17 when a total of only 939 sets had been fished.

The theory of competing risks offers a modeling strategy for describing the endogenous dependence of allowable fishing effort on the risk of hitting a cap. The idea is to model the takes of loggerhead and leatherback turtles in each period as conditionally independent Poisson processes given the respective BPUE for the two species and the level of fishing effort. Fishing effort may either end due to hitting one of the two caps, or for other reasons which include economic considerations which affect the ongoing viability of fishing effort and engineering limits on the amount of effort which can be achieved by the fleet in a single season.

Let $S_\tau(n)$ denote the effort survival function for total effort n in a given season, defined as the probability that fishing effort for the current season will survive to n sets. It is possible for fishing effort to end due to hitting either of the caps or due to other reasons. Let $S_j(n)$ denote the effort survival function for hitting turtle cap j, where $j = 1$ denotes loggerheads and $j = 2$ denotes leatherbacks. Further let the effort survival function for economic and engineering risks to effort cessation (besides hitting a turtle take cap) be denoted $S_Z(n)$. If the three risks are assumed to be independent[4], the effort survival function is given by

$$S_\tau(n) = S_1(n)S_2(n)S_Z(n). \tag{12}$$

A simple but conservative assumption about the survival function for risk that effort ends for other reasons besides reaching a turtle cap is that $S_Z(n) = 1$ for $n \leq Z_{max}$ and $S_Z(n) = 0$ for $n > Z_{max}$. Estimated effort and predicted turtle takes which follow from this simplifying assumption are conservative compared to those which would follow from a richer model of economic effort which more accurately reflected economic and engineering considerations on the risk that effort does not survive to Z_{max}.

The probability that effort survives to n sets before hitting turtle cap j is equivalent to the probability that the cap has not been reached

[4]This assumption should be relaxed if, for example, the probability that effort continues is conditionally dependent on how close the current turtle take levels are to reaching a cap.

by the time $n-1$ sets are fished:

$$S_j(n) = \int_0^\infty F(c^{(j)} - 1|n-1, \theta) p(\theta \,|\, \mathbf{y}_j, \mathbf{Z}) d\theta, \qquad (13)$$

where the Poisson c.d.f. $F(c^{(j)} - 1|n-1, \theta)$ is evaluated at one less set than the take cap $c^{(j)}$ on turtle species j, then integrated over the posterior density for species j.

2.5 Posterior Predictive Distributions

Given the preceding development, it is possible to compute posterior predictive distributions for allowable fishing effort and for turtle takes of the two species of concern. The posterior predictive distribution (PPD) for effort is defined as the probability that effort ends at exactly n sets. It is simply obtained as the forward first difference of the effort survival function:

$$\tilde{f}_\tau(n) = S_\tau(n) - S_\tau(n+1). \qquad (14)$$

The CPPD for in season bycatch of turtle species $j = 1, 2$ may be obtained by integrating the truncated poisson likelihood function over the posterior density for BPUE of species j at effort level n and cap level c is given by:

$$\tilde{p}_j(y \,|\, n, c) = \int_0^\infty \frac{f(y \,|\, n, \theta)}{F(c \,|\, n, \theta)} p(\theta \,|\, \mathbf{y}_j, \mathbf{Z}) d\theta \qquad (15)$$

where $g_j(y|n, \theta, c) = \frac{f(y|n,\theta)}{F(c|n,\theta)}$ denotes the truncated Poisson likelihood function for species j with truncation at c under the assumption that n sets of effort have occurred.

Given the PPD for effort and the CPPD for bycatch, the (unconditional) PPD for turtle bycatch is obtained as the expectation of the CPPD with respect to the level of fishing effort:

$$\begin{aligned} \tilde{p}_j(y \,|\, c) &= E_Z[\tilde{p}_j(y \,|\, Z, c)] \\ &= \sum_{n=0}^{Z_{max}} \tilde{p}_j(y \,|\, n, c) \tilde{f}_\tau(n), \end{aligned}$$

where $Z_{max} = \infty$ for the case of no overall effort limit.

3 Policy Analysis

The Bayesian view holds that the posterior distribution gives a complete summary of the inference about the parameter in light of the observed data and the probability model in use. Posterior inference was used to compare the current policy (loggerhead cap of 17, leatherback cap of 16 and effort limit of 2120) and the proposed policy (loggerhead cap of 46, leatherback cap of 19 and elimination of the effort limit).

Though the proposed regulatory change would eliminate the effort limit entirely, there are implicit limits which could constrain effort including a limited number of permits, engineering constraints on the amount of effort which could be fished in one season under a single permit, 100 percent observer coverage requirements and economic reasons such as high fuel costs or low swordfish prices which could result in a decision to stop fishing before the end of the season. In order to illustrate the effect of turtle caps in eventually leading to the cessation of effort, the level of effort under the proposed regulatory change is assumed to have an upper limit of 4240 sets, roughly equal to the average annual effort in the years before regulation. The results should be interpreted as a conservative (worst case) illustration, as there are many reasons aside from hitting a turtle cap that effort could end before 4240 sets.

3.1 Posterior Predictive Distributions

Matlab routines were used to compute PPDs and produce graphical comparisons to illustrate the effect of the policy change on allowable effort and turtle bycatch.

The effort survival function shifts significantly to the right when the turtle caps are relaxed from the current to the proposed policy. This shift reflects the combined impact of loosening the stochastic constraint on effort imposed by the turtle caps and relaxing the overall effort constraint.

The posterior predictive distributions of loggerhead takes have modes at the cap levels under both the current and proposed policies, indicating that effort is likely to be constrained by hitting the loggerhead take cap under both scenarios. The relaxation of the effort constraint and assumption that effort will continue up to as many as 4240 sets under the proposed policy suggest that a sizable increase in loggerhead takes is a possibility if regulatory constraints are relaxed.

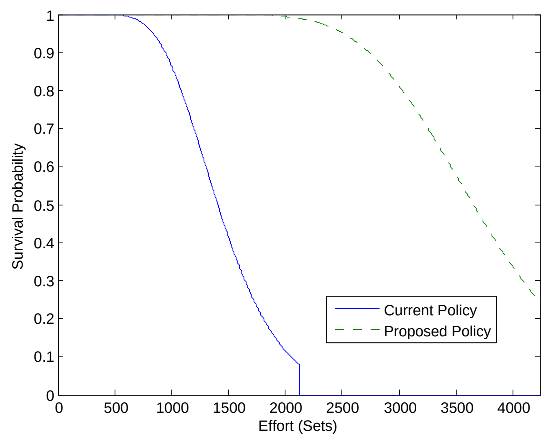

Figure 1: Effort survival functions

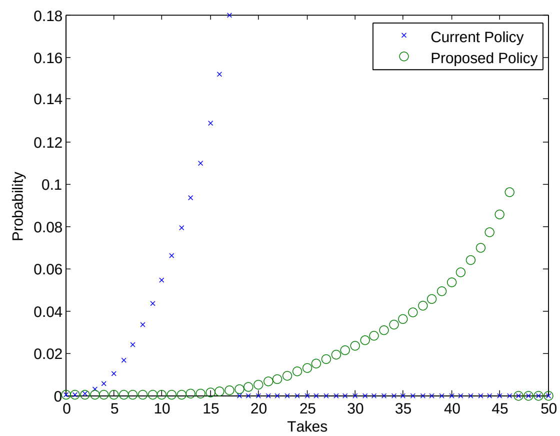

Figure 2: Posterior predictive distributions of loggerhead takes

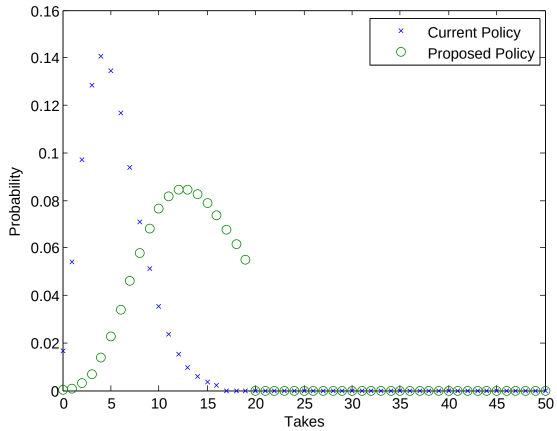

Figure 3: Posterior predictive distributions of leatherback takes

	Current Policy	Proposed Policy
Effort	1437.3 (387.5)	3579.6 (591.2)
Loggerhead Takes	13.4 (3.2)	37.9 (7.0)
Leatherback Takes	5.4 (3.0)	12.4 (4.0)

Table 1: Expected Effort and Turtle Takes

A similar shift to the right in the posterior predictive distribution of leatherback takes results from the relaxation of the caps. The probability of effort terminating at the leatherback cap shows a sizable increase under the proposed policy, suggesting the effect of the increase to the cap is more than offset by the increase in expected effort.

3.2 Point Estimates

Point estimates may be computed using appropriate summary statistics for the posterior predictive distribution (such as the mean or the standard deviation). The following table illustrates point estimates of the expected levels of effort and turtle bycatch with standard errors in parentheses. Two scenarios are compared: The current policy includes a loggerhead cap of 17 and a leatherback cap of 16 with an overall effort limit of 2120 sets. The proposed policy features a loggerhead cap of 46 with a leatherback cap of 19 and an elimination of the effort limit. For the proposed policy, I again assume effort will end at 4120 sets if no cap has been reached in order to reflect other known constraints on effort.

The above table shows predicted effort and turtle takes with standard deviations in parentheses[5]. The proposed relaxation of regulatory constraints under the proposed policy change is expected to significantly increase the allowable levels of effort and turtle bycatch compared to current policy. Standard deviations also generally increase, although the increase in standard deviation in the case of leatherback takes is mitigated by the concentration in the predictive distribution towards the cap. The general conclusion is that an increase in allowable effort comes at the price of higher incidental take rates of

[5]Predicted values are expectations over the related PPDs, and standard deviations are the standard deviations of the PPDs.

loggerhead and loggerhead turtles.

4 Conclusions

The need to balance fishing opportunities against the risk of endangered species take represents a challenge for fishery management which depends on reasonable predictions of endangered species take as a function of fishing effort, and of effort which could be achieved under the type of bycatch reduction constraints which are commonly utilized, such as a quota with one or more protected species take caps. This paper has set forth and demonstrated a methodology for estimating predictive distributions of bycatch and effort when a fishery is regulated by some combination of effort quota and turtle bycatch caps. The methodology was used to predict the potential impact of a proposed regulatory change.

The methodology developed herein can potentially be used in conjunction with cost and earnings data to estimate the shadow price of the turtle caps in terms of fishing profitability, or to determine the effect of regulatory constraints on the economic viability of a fishery. A basic question that could also potentially be addressed is that of what regulatory policy is optimal from the dual perspective of conservation goals and economic viability. Merely meeting the strict requirements of the ESA and other environmental laws may fail to achieve an optimal balance between conservation and economic objectives.

A direction for further research is to develop a more realistic model of economic effort. The approach presented here relies on the simplifying assumption that effort will continue until a binding cap or quota is reached. Consequently, the effect of the proposed relaxation of regulatory constraints on effort and turtle bycatch should be viewed as a worst case scenario for what might occur rather than an unbiased prediction. Modeling the endogenous response of fishermen's choice of effort to different policy regimes or to stochastic variation in the conditions which determine profitability of continued effort is a challenge. The simplified approach presented here is conservative in producing upper bounds on the levels of target species take and bycatch compared to the estimates that would be obtained by allowing for the possibility that effort may end before it hits a regulatory limit.

Another possible direction for future research is to better capture the range of potential variation in turtle CPUE across a range of underlying stock levels, oceanographic conditions, gear types, vessel sizes, fishermen behavior, spatiotemporal distributions of fishing effort, and other underlying factors which potentially cause CPUE to vary. The quantification of these various factors is an empirical problem which has already been addressed by other research efforts, but the question remains of how best to incorporate the range of potential variation in CPUE into the framework presented here. Failing to take these sources of variation into proper account may result in posterior predictive distributions which produced biased forecasts that understate the variance, as the only sources of variance taken into account in the methodology set forth here are inferential uncertainty about the true value of the CPUE parameter, and the endogenous response of effort to regulatory limits.

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