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# INCORPORATING COLLATERAL INFORMATION USING AN ADAPTIVE MANAGEMENT FRAMEWORK FOR THE REGULATION OF TRANSGENIC CROPS

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**ABSTRACT**

A lack of data often makes biological management decisions difficult and has been an area of contention in the debate over the approval of transgenic crops. Our knowledge of natural systems is limited and our ability to gain additional information, quickly and effectively, is often handicapped by statistical complexity. To adequately cope with this requires new approaches and models that integrate decision-making and management. This paper describes one possible approach to the integration of decision-making and management, which may have application for the regulatory approval of transgenic crops. In many situations countries wishing to approve transgenic crops will have limited data on the environmental performance of the crop. The approach outlined in this paper looks at how related information, possibly collected from other countries, might be used to help inform decisions about the approval of transgenic crops. This is done within an integrated decision-making and management framework.

Keywords: Bayesian estimation, collateral data, inference, GMO

**TABLE OF CONTENTS**

# INCORPORATING COLLATERAL INFORMATION USING AN ADAPTIVE MANAGEMENT FRAMEWORK FOR THE REGULATION OF TRANSGENIC CROPS

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## 1. INTRODUCTION

A lack of data often makes biological management decisions difficult (Hilborn & Walters 1992; Hilborn & Mangel 1997). Our knowledge of exploited systems is limited, and the ability to gain additional information in a timely fashion is handicapped by the statistical complexity of many problems (Ludwig 1993; Hilborn & Mangel 1997). Detailed data sets with which to estimate biological parameters are lacking for most species and systems (Burgman et al. 1993), and this makes the use of quantitative methods, such as population viability analysis, problematic (Ludwig 1999; Coulson et al. 2001). It is of great practical importance that, in situations where we have little direct data, we enhance our knowledge of fecundity, survivorship, density-dependence mechanisms, responses to disturbance, and other ecological parameters with data from closely related species or from the same species at different sites—that is, from collateral data. Currently no structured and transparent processes for incorporating collateral information exist.

Collateral data may be defined as related knowledge that informs a decision about the value of a parameter. The ordinary approaches to statistical estimation, least squares

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and maximum likelihood, do not easily allow related quantitative data to be incorporated in an estimate. For example, we may have an estimate of mortality for a congener of a species but no direct estimates. Given anecdotal observations, and some natural history data, biologists may be prepared to make a guess at the parameter. If we then take some field measurements of the target species, should we dispense with the data from the related species? Standard methods would say yes, but collateral information has value, although intuitively this value should decrease as more data on the species of interest is obtained. There are many analogous problems in the insurance industry, and there is a long history in actuarial applications of making use of collateral data to improve judgments (Norberg 1979). In many circumstances, actuaries judge novel risks from sparse data, just as biologists do. Insurance companies set premium rates in situations where they have little or no experience of claim frequencies or claim sizes (Waters 1993). Actuarial credibility theory, when combined with the financial managements process based on the actuarial control cycle (Fig. 1), is used to incorporate collateral insurance data and to update assumptions (Goford 1985, Waters 1993, Hart et al. 1996).

Actuaries originally developed credibility theory as a solution to the problem of calculating premiums for short term insurance contracts. An insurance company charges a premium composed of a component for risk, such as the probability of fire, theft, or death during the insurance period, and an allowance for expenses and profit.

The risk component is referred to as the risk premium. The central problem for the company is what to charge for the risk. The company can calculate the risk premium directly from the history of claims of that particular individual or class of individuals wanting insurance, or it can calculate the risk premium based on the insurance company's experiences of "similar" risks. In many situations it is impossible to calculate the risk premium from history because the number of claims is too small. In this situation, credibility theory is used to incorporate collateral data to improve estimates (Hart et al. 1996).

The method uses a linear combination of information from the risk of interest with information from collateral risks to calculate a weighted average:

$$C = Z \times \mu_D + (1 - Z) \times \mu_C, \tag{1}$$

where C is the credibility estimate, Z ($0 \leqslant Z \leqslant 1$) is the credibility factor or weight given to direct data, $\mu$ D is an estimate of the parameter on direct data, and $\mu$ C is an estimate of the parameter based on collateral data (Herzog 1994; Hart et al. 1996). Intuitively, the more direct data we have, the more reliance should be placed on it and the less reliance on collateral data. As time passes and more direct data are collected, the credibility factor should increase, giving more weight to the direct data and less to the collateral data (Waters 1993).

The different approaches to credibility theory determine different ways of estimating *Z*. Early attempts to develop these ideas resulted in "American credibility theory," or "limited fluctuation credibility theory," based on formulae that do not have a rigorous mathematical basis. Later developments in the 1960s led to "European credibility theory," or "empirical Bayes credibility," and "greatest accuracy credibility" (Buhlmann 1967, 1969).

Empirical Bayes Credibility is based on parametric empirical Bayes methods described by Efron and Morris (1973, 1975). More recently, Ver Hoef (1996) described applications of empirical Bayes methods in ecology. Actuaries use a modification of the empirical Bayes approach that makes it easier to apply by linearizing the Bayes estimator and incorporating collateral data (Waters 1993; Klugman et al. 1998).

We sought to describe the tools used by actuaries that may have applications in biology and to assess their potential for incorporating collateral data in an adaptive management framework. Actuaries make two key assumptions to develop relatively simple and tractable credibility formulae for applied work: (1) it is assumed that the best linear approximation to the Bayesian formulae is a reasonable approximation, and (2) when formulae are developed for including collateral data, it is assumed that the same distributional form applies to the collateral data and the data of interest. We explore these assumptions in the discussion and provide some evidence to suggest that the credibility approach is a worthy addition to the biologist's toolbox.

## 2. TECHNICAL DEVELOPMENT

### MODEL DEVELOPMENT AND APPLICATIONS

This section is structured around the historical development of credibility theory. First, we look at the motivation for credibility theory and early approaches to the problem, collectively known as American credibility. Second, we look at pure Bayesian approaches to the problem, which attempt to be more mathematically rigorous and replace earlier ad hoc methods. Pure Bayesian approaches assume, however, that the prior distribution is known. Third, we look at empirical Bayes credibility theory, which makes less stringent assumptions about the prior distribution, requiring only knowledge of the distributional family of the prior to develop the formulae for including collateral data. Finally, we provide an example.

AMERICAN CREDIBILITY THEORY

American credibility theory provides a simple introduction to the concepts of credibility theory by answering the question "What amount of direct data is required for $Z$ to be one so that the collateral data to be ignored?" The criterion used is that the relative error between the direct estimate and the true value should be less than a given amount with given probability. 'Fully credible' implies that the data are sufficiently precise and accurate to satisfy prescribed levels of reliability; restating this mathematically, the data are said to be fully credible ($k$, $p$) if:

$$P\left( |\hat{\beta} - \beta| \leq k\beta \right) \geq p \qquad (2)$$

where $\hat{\beta}$ is the direct estimate, $\beta$ is the true value, $p$ is the probability and $k$ is the allowed error. The value $\left|\hat{\beta} - \beta\right|$ is the tolerance allowed by a decision-maker. It represents a goal of how close to the correct parameter the observer would like to be (in standardised units); and $p$ represents another user-specified value. It represents the reliability with which one wants to be within a given range.

The theory is best illustrated by an example. Suppose we want to estimate mortality of an insect exposed to Bt-toxin and assume a Poisson distribution of deaths (Akcakaya 1991) then $M \sim Poisson(T\lambda)$ where $M$ is the number of deaths and $T$ is the period of observation. The data are fully ($k$, $p$) credible if

$$P(\left| M/T - \lambda \right| \leq k\lambda) \geq p\,. \qquad (3)$$

With some rearrangement (3) becomes

$$P\left(\left|\frac{M - T\lambda}{(T\lambda)^{1/2}}\right| \leq k(T\lambda)^{1/2}\right) \geq p \qquad (4)$$

For example suppose that it is important to be at least 80% certain that the estimate of $M$ is within 5% of the true value. Substituting $k = 0.05$ and $p = 0.80$ and using the normal approximation to the Poison distribution, we need to observe about 657 deaths to be fully credible.

Suppose that data are available for a related species with similar general ecology and 100 deaths are observed over the period $T$. If the assessment of the mortality rate is to benefit from collateral data then it is necessary to determine $Z$. One formula that has proven to be empirically usefully in actuarial applications is (Waters 1983)

$$Z = \min\left(\left(\frac{M}{m_o}\right)^{1/2}, 1\right) \qquad (5)$$

where, in this case, $M$ is the number of observed deaths and $m_o$ is the number of deaths required to be fully credible by some standard. $Z$ is then calculated as 0.15 according to (6).

$$Z = \min\left(\left(\frac{100}{657}\right)^{1/2}, 1\right) \qquad (6)$$

In this case the estimated mortality is heavily reliant on the relatively extensive collateral data.

This example makes some of the problems with American Credibility Theory evident. Equation (5) is not derived from any fundamental principle. The parameter '$m_0$' is based on an arbitrary credibility standard and, perhaps most importantly, it ignores the reliability of the collateral data. Bayesian Credibility addresses these problems by incorporating the reliability of prior data in a mathematically defensible way (Waters 1993). A pure Bayesian approach relies on the subjective choice of the prior distribution for determining the reliability of collateral data (Cox and Hinkley 1974). This may be problematic.

## EMPIRICAL BAYES CREDIBILITY THEORY

The ideas behind empirical Bayes are best illustrated by way of examples. The theoretical development of the formulae can be found in (Waters 1993, Klugman et al. 1998, Appendix A). In this section we present without proof the credibility estimators.

The theory is illustrated in terms of mortality, which is a familiar concept to biologists. However, the theory can be applied more widely as will be seen in the example on crop yields.

Suppose that we have $D$ populations, whose annual mortality rates depend on fixed, unknown, parameters, $\theta_1$, $\theta_2$, ..., $\theta_D$, with mean rates $m(\theta_1), m(\theta_2), \ldots, m(\theta_D)$, respectively, where $m$ is a known (assumed) function. We want to estimate one of these mean rates, say $m(\theta_D)$. For each population, $i$, we have paired observations of deaths and population size ($Y_{ij}$, $N_{ij}$), and thus annual rates $X_{ij} = Y_{ij}/N_{ij}$, for $j$ in a set of years $S$. The matrix is shown in equation (7). We assume that, given $\theta$, the variables $\{X_{ij}, j \in S\}$ are mutually independent and $X_{ij}$ has mean $m(\theta_i)$ and variance $s^2(\theta_i)$. We now make the Bayesian assumption that the $\theta_1, \theta_2, \ldots, \theta_D$ are independent, identically distributed random variables.

$$\begin{array}{cccccc} & \multicolumn{5}{c}{\textit{TIME}} \\ & & 1 & 2 & \cdots & S \\ & 1 & Y_{11}, N_{11} & Y_{12}, N_{12} & \cdots & Y_{1S}, N_{1S} \\ POP & 2 & Y_{21}, N_{21} & Y_{22}, N_{22} & \cdots & Y_{2S}, N_{2S} \\ & \vdots & \vdots & \vdots & \vdots & \vdots \\ & D & Y_{D1}, N_{D1} & Y_{D2}, N_{D2} & \cdots & Y_{DS}, N_{DS} \end{array} \tag{7}$$

A purely Bayesian approach assumes the distribution of the $\theta$s to be known, and uses the data on population $D$ to calculate the conditional distribution of $\theta_D$ and hence of $m(\theta_D)$. An Empirical Bayesian estimates the distribution of the $\theta$s from equation (7), and then proceeds like a Bayesian. Empirical Bayes Credibility Theory attempts the same thing, but estimates only $\mu = E(m(\theta))$, $\sigma^2 = E(s^2(\theta))$ and $V(m(\theta))$, the variation of the $m(\theta)$ between populations, rather than the full distribution of the θ's. Waters (1993) suggests the estimators:

$$\mu : \hat{\mu} = \sum_j \frac{N_{i+} X_{i\bullet}}{N_{++}} \tag{8}$$

$$\sigma^2 : \hat{\sigma}^2 = \frac{1}{D(S-1)} \sum_i \sum_j N_{ij} \left(X_{ij} - X_{i\bullet}\right)^2 \tag{9}$$

$$V(m(\theta)) : \hat{V}(m(\theta)) = \frac{1}{N^*} \left\{ \frac{\sum_i \sum_j N_{ij} \left(X_{ij} - X_{\bullet\bullet}\right)^2 - \hat{\sigma}^2}{(DS-1)} \right\} \tag{10}$$

where the "+" indicates a sum over the missing subscript, so

$$N_{i+} = \sum_j N_{ij} \text{ and } N_{++} = \sum_i N_{i+}$$

the "$\bullet$" indicates a weighted average, so

$$X_{i\bullet} = \frac{\sum_j N_{ij} X_{ij}}{N_{i+}} \quad \text{and} \quad X_{\bullet\bullet} = \frac{\sum_i N_{i+} X_{i\bullet}}{N_{++}} = \frac{\sum_i \sum_j N_{ij} X_{ij}}{N_{++}}$$

and

$$N^* = \frac{\sum_i N_{i+}\left(1 - \frac{N_{i+}}{N_{++}}\right)}{(DS - 1)}.$$

Waters (1993) then proposes

$$Z : \hat{Z}_i = \frac{\sum_j N_{ij}}{\sum_j N_{ij} + \frac{\hat{\sigma}^2}{\hat{V}(m(\theta))}} \tag{11}$$

giving the credibility estimate of mortality as:

$$C_i = Z_i X_{i\bullet} + (1 - Z_i)\hat{\mu} \tag{12}$$

Equation (8) seems reasonable because it is (total deaths)/(total population sizes). Equation (9) appears plausible because it is a modification of the within-group variance from a single-factor ANOVA model. Equation (10) can be negative, as can a standard estimate of between-group variance in ANOVA. Waters (1993) suggests that when (10) is negative actuaries assume it is zero. As in the ANOVA case, the error of this biased estimator is sometimes smaller and never larger than that of the unadjusted, unbiased estimator.

## 3. APPLICATIONS

ESTIMATES OF MORTALITY USING RELATED SPECIES, OR SPECIES WITH A SIMILAR LIFE-HISTORY

Suppose it is necessary to judge the likely future populations of Powerful Owls and there are data for three raptor species (Table 1). Such a situation might arise were we want to make assumptions about the potential impact of the introduction of an insect protected plant, which might affect the abundance of food resources for birds.

**Table 1--Simulated numbers of deaths with the corresponding population estimates (deaths/population estimate) for four raptor species. Weights were obtained from McCarthy *et al.* (1999).**

| | YEAR OF OBSERVATION | | | | |
|---|---|---|---|---|---|
| SPECIES | MASS | 1 | 2 | 3 | 4 |
| BARN OWL (*TYTO ALBA*) | 370G | 30/100 | 40/120 | 33/100 | 29/97 |
| POWERFUL OWL (*NINOX STRENUA*) | 350G | 1/11 | 2/10 | 0/10 | 1/12 |
| GREAT HORNED OWL (BUBO VIRGINIANUS) | 280G | 16/100 | 16/110 | 15/90 | 10/70 |

Circumstances such as this provide an opportunity for the Credibility Theory estimate for Powerful Owl mortality to be derived.

We calculate

$$\sum_j N_{ij}\left(X_{ij} - X_{i\bullet}\right)^2 \qquad \sum_j N_{ij}\left(X_{ij} - X_{\bullet\bullet}\right)^2$$

| | | |
|---|---|---|
| BARN OWL (*TYTO ALBA*) | 0.109 | 3.053 |
| POWERFUL OWL (*NINOX STRENUA*) | 0.202 | 1.039 |
| GREAT HORNED OWL (*BUBO VIRGINIANUS*) | 0.035 | 2.313 |

$$\hat{\mu} = \frac{(30 + \cdots + 10)}{(100 + \cdots + 70)} = 0.233 \tag{13}$$

$$\hat{\sigma}^2 = \frac{(0.109 + 0.202 + 0.035)}{3 \times (4-1)} = 0.038 \tag{14}$$

$$V^2(m(\theta)) = \frac{\left(\frac{(3.053 + 1.039 + 2.313)}{3 \times 4 - 1} - 0.038\right)}{41.212} = 0.013 \tag{15}$$

Substituting the results from (14) and (15) into (11) gives $Z = 0.99$ and using (12) gives a mortality estimate for the Powerful Owl in the next time period of 0.10 or 1 death per 100 birds.

## 4. DISCUSSION AND CONCLUSIONS

In population viability studies (Boyce 1992), and in probabilistic risk and reliability analysis generally (Kaplan 1992), it is rare that sufficient experience and sufficient data exist for us to be able to determine all important parameters directly. In many circumstances, because of the lack of direct data, expert judgment replaces direct observation (Kaplan 1992). Such judgements are intrinsically uncertain and in population viability analysis studies the uncertainty in parameter estimates can be modelled using Bayesian techniques (e.g. Ludwig 1996, Wade 2000).

To illustrate the Bayesian approach to population viability analysis (PVA) consider an example in which a PVA depends on some parameter $\phi$ which is thought to be distributed N($\psi$, $\sigma^2$). A Bayesian analysis will treat $\psi$ as a random variable, say, $\psi$ is distributed N(100, 10). This assumption is used to generate instances of $\psi$ i.e. $\psi_1, \psi_2, \ldots, \psi_n$ which would then be used to generate values for $\phi$ i.e. $\phi_1, \phi_2, \ldots, \phi_n$. In this way uncertainty about $\psi$ is included in the analysis. The analysis then provides information about the probability of extinction, given views about the uncertainty of $\psi$. However in practical applications we may not really know how $\psi$, or any other parameter, is distributed. In such situations it is important that we manage the emerging uncertainty by a process such as the control cycle (Figure 1) and monitor for departure from our best estimates. In such situations Credibility Theory may be used to set the best estimates from collateral data.

The motivation behind Actuarial Credibility Theory appears to be the desire for a simple and practical basis for combining collateral data in parameter estimates. There is considerable conceptual appeal in having a method that combines collateral data by using a linear combination (weighted average) of information from the risk of interest with information from collateral risks.

The development of Actuarial Credibility Theory started with ad-hoc methods, known as American credibility, for calculating $Z$ using simple formulae. American credibility theory provided answers to the question "What amount of direct data is required for $Z$ to be one so that the collateral data can be ignored?" The development of more sophisticated mathematical techniques led to Bayesian Credibility theory which addressed the problems of ad hoc formulae by incorporating the reliability of prior data in a mathematically defensible way (Waters 1993). However a pure Bayesian approach relies on the subjective choice of the prior distribution for determining the reliability of collateral data (Cox and Hinkley 1974). This may be problematic. Empirical Bayes Credibility addresses this problem by making less stringent assumptions about the prior distribution, requiring only knowledge of the distributional family for the prior.

In order to obtain tractable formulae for calculations, instead of using the Bayes estimate, the Actuarial profession adopted the best linear approximation to the Bayes estimate. In many instances where the statistical distributions are drawn from the linear exponential family, the Bayes estimate is linear and the Credibility estimate equals the Bayes estimate (Klugman et al. 1998). Klugman et al. (1998) argue that although additional error is caused by the linear approximation, if numerous estimations are performed then, provided these errors cancel out over time, it may be a reasonable assumption. Essentially, these methods provide simplicity and tractability, with some cost of accuracy. Circumstances will determine if the benefits exceed the costs.

The inclusion of collateral data depends on another simplifying assumption, that the collateral and direct data are drawn from statistical populations that are essentially alike (i.e. the same distributional family is assumed). This approach should be familiar to biologists who routinely use analysis of variance or other linear statistical models (Searle 1979). It is clearly possible under Bayes and Empircal Bayes approaches to use different families of prior distributions and not make this simplifying assumption. However, for all but the simplest cases, this results in complex formulae which therefore may have limited application in applied work.

It also seems plausible, but not essential, that equivalent parameters for ecologically similar populations will be adequately represented by statistical populations that are essentially alike. The important advantage gained by this assumption is simple, tractable formulae. However, the extrapolations facilitated by Credibility Theory, while transparent and repeatable, need to be tempered by whatever other evidence can be brought to the problem on the extent to which this assumption is justified. It may be reasonable to equate a population for which there are no direct data with other species or other locations, especially if the cause for decline of a rare species is known and is unrelated to vital rates or other unique properties. If the population has been hunted to near extinction, for instance, then data from other species may provide useful collateral data to judge potential recovery rates.

Credibility Theory is an important and relatively explicit technique in general insurance practice for incorporating collateral data. Equating similar species with a species at risk has many analogues in insurance but unfortunately; we found it impossible to assess the predictive power of Credibility Theory because insurance companies hold the application in commercial confidence (pers. comm. Aldois Gisler). However, further work in this area may yield biologists with new tools that may provide transparent and defensible techniques for incorporating collateral data. We will not be able to judge the utility of Credibility Theory for applications in conservation biology until a body of evidence accumulates documenting successes and failures.

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## APPENDIX A – EMPIRICAL BAYES CREDIBILITY THEORY

The ideas of Empirical Bayes Credibility are best developed using a simple model for estimating population mortality. Let $Y_1, Y_2 \ldots Y_n$ denote the number of deaths from a specific population over successive periods (say years); let $N_1, N_2 \ldots N_n$ denote the corresponding population sizes; and let

$$X_j = \frac{Y_j}{N_j}. \qquad \text{(A1)}$$

Then the sequence of random variables denoted by $X_1, X_2 \ldots X_n$ , represent the mortality experienced by animals in the population in successive periods. These values constitute the direct data.

Let the distribution of $X_j$ depend on a fixed, unknown, parameter $\theta$. Uncertainty about the value of the parameter $\theta$ is dealt with by regarding it as a random variable. Given the random choice of $\theta$, the $X_j$'s are assumed to be independent, all with the same mean, $m(\theta)$, and with variance $s^2(\theta)$.

First consider the Bayesian problem of estimating $m(\theta)$ from $X_1, X_2, \ldots X_n$ when the distribution of $\theta$ is assumed known. The best (least squared error) linear estimate is achieved by minimising (Buhlmann 1967, 1969, Waters 1993)

$$I = E\left(\left(m(\theta) - \left(a_0 + \sum_j a_j X_j\right)\right)^2\right) \qquad \text{(A2)}$$

where the expectation is over both $\theta$ and the $X$'s. Differentiating (A2) with respect to $a_0$, $a_1, a_2, \ldots, a_n$ and equating the partial derivatives to zero gives

$$\frac{\partial I}{\partial a_0} = 0 \Rightarrow E\left(m(\theta) - a_0 - \sum_j a_j X_j\right) = 0$$

which gives

$$a_0 = E(m(\theta))\left(1-\sum_j a_j\right).$$

Using

$$E(X_j) = E(E(X_j \mid \theta)) = E(m(\theta)) = \mu$$

gives

$$a_0 = \mu\left(1-\sum_j a_j\right) \tag{A3}$$

and

$$\frac{\partial I}{\partial a_k} = 0 \Rightarrow E\left(X_k\left(m(\theta) - a_0 - \sum_j a_j X_j\right)\right) = 0\,.$$

Using

$$E(X_j m(\theta)) = E(m(\theta)E(X_j \mid \theta)) = E(m^2(\theta)) = V(m(\theta) + \left(E(m(\theta)\right)^2$$

$$E(X_k X_j) = E(E(X_k X_j \mid \theta)) = E(E(X_k \mid \theta)E(X_j \mid \theta))$$
$$= E(m^2(\theta)) = V(m(\theta)) + (E(m(\theta)))^2$$

$$E(X_j^2) = E(m^2(\theta) + s^2(\theta)/N_j) = E(m^2(\theta)) + \sigma^2/N_j$$

gives

$$V(m(\theta)) + (E(m(\theta)))^2 - a_0 E(m(\theta)) - \sum a_j (V(m(\theta)) + (E(m(\theta)))^2) - a_k \frac{\sigma^2}{N_k} = 0$$

which simplifies to

$$a_k = \frac{N_k V(m(\theta))(1-\sum_j a_j)}{\sigma^2} \tag{A4}$$

Summing both sides gives

$$\sum_k a_k = \frac{V(m(\theta))(1-\sum_j a_j)}{\sigma^2}\sum_k N_k$$

Solving for $\sum a_j$ and substituting into (A3) and (A4) gives

$$a_0 = \frac{\sigma^2 \mu}{\sigma^2 + N_+ V(m(\theta))} \qquad \text{(A5)}$$

$$a_j = \frac{N_j V(m(\theta))}{\sigma^2 + N_+ V(m(\theta))} \qquad \text{(A6)}$$

where

$$V(m(\theta)) = E(m^2(\theta)) - E^2(m(\theta)) \text{ and } N_+ = \sum N_j$$

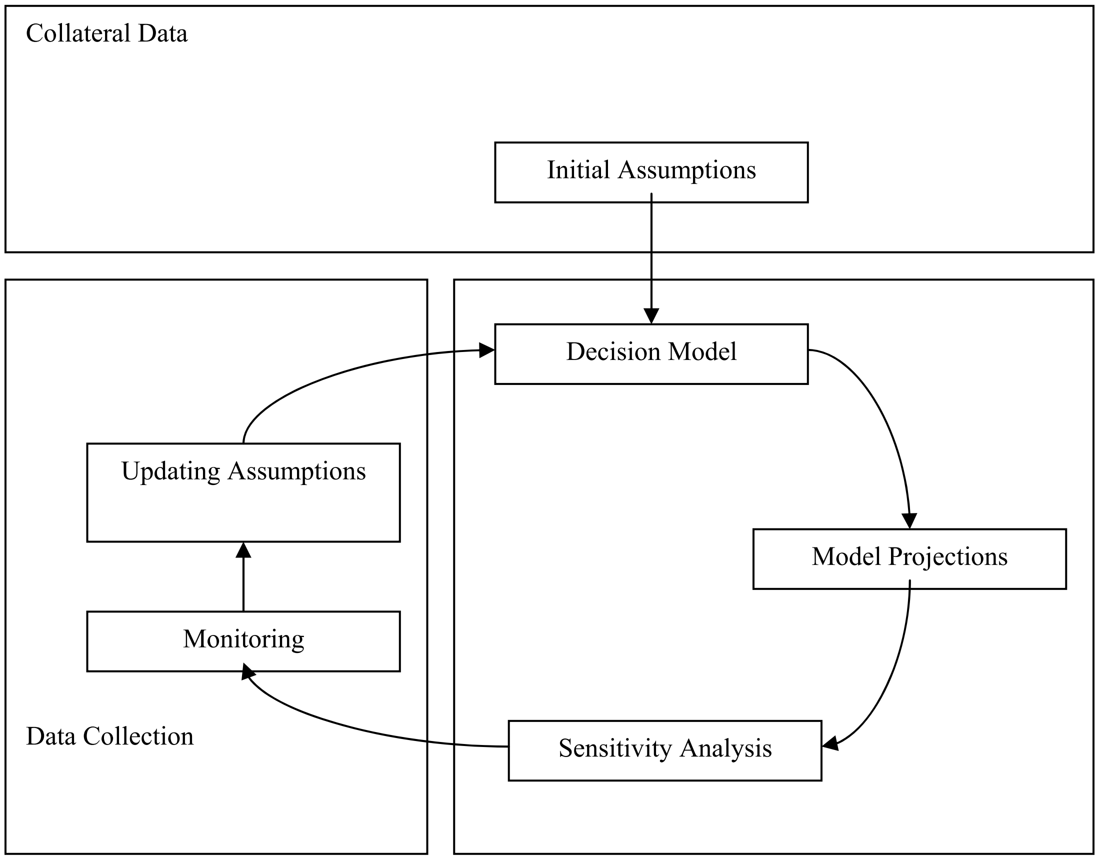
Thus the Bayesian Credibility estimator of *m(θ)* is

$$a_0 + \sum a_j X = \frac{\left(\mu\sigma^2 + V(m(\theta))\sum N_j X_j\right)}{\left(\sigma^2 + N_+ V(m(\theta))\right)}$$

$$= ZX + (1-Z)\mu \qquad \text{(A7)}$$

where $Z = \frac{N_+ V(m(\theta))}{\sigma^2 + N_+ V(m(\theta))}$ and $X = \frac{\sum_j N_j X_j}{N_+}$.

**Figure 1--The Control Cycle adapted from (Goford 1985). The Control Cycle shows an integrated way to manage risk. A model is developed and used to obtain projections. The sensitivity of the model is also used to identify important assumptions, which are then monitored and updated and feedback into the cycle**



LIST OF EPTD DISCUSSION PAPERS

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