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Model Used

First studied in Operation Research literature, POMDP provides an interesting way of reasoning about trade-offs between actions to gain rewards and actions to gain information.

In our case, solving a POMDP is finding a strategy $\pi : B \times \tau \mapsto \mathrm{A}$ mapping an allocation of resource given a current belief state and a time-step. An optimal strategy maximizes the expected sum of rewards over a finite time horizon, *T*. This expected summation is also referred to as the value function. A value function essentially ranks strategies by assigning a real value to each b. Using the Bellman principle of optimality and the previously-defined POMDP parameters, we can calculate the optimal *t*-step value function from the (*t*–1)-step value function:

$$V_0^*(b) = \max_{a \in \mathrm{A}} \left[\sum_{s \in S} R(s,a) \Pr(s|b) \right], \quad (1)$$

$$V_t^*(b) = \max_{a \in \mathrm{A}} \left[\sum_{s \in S} R(s,a) \Pr(s|b) + \sum_{s \in S} \sum_{s' \in S} \sum_{z \in Z} \Pr(s|b) P(s'|s,a) O(z|s',a) V_{t-1}^*(b_z^a) \right], \quad (2)$$

where $Pr(s|b)$ represents the probability of being in state *s* given a belief state *b*, and $b^a{}_z$ is the belief state assuming action *a* and observation *z*. Equation (1) maximises the expected sum of instantaneous rewards when there is no time left to manage for the species. Similarly when there is *t*-steps to go, equation (2) maximises the instantaneous rewards and the future expected rewards for the remaining *t*-1-steps.

The optimal solution π can be represented in two different ways. We can either apply directly the strategy function for each belief state we are in (Fig. 2) or we can represent the optimal strategy as a policy graph (Fig. 1). The policy graph automatically generates all the possible transitions over time given the performed action and the new observation whereas the use of strategy functions requires updating the belief state using Bayes' rule given the performed action and the new observation. After action performed *a* and observation received *o*, the updated belief b_o^a can be calculated from the previous belief *b*:

$$b_o^a(s') = \Pr(s'|b,a,o) \quad , \tag{3}$$

$$b_o^a(s') = \frac{Z(o|a,s')\sum_{s\in S} P(s'|s,a)b(s)}{\Pr(o|a,b)} \quad , \tag{4}$$

$$\text{With } \Pr(o|a,b) = \sum_{s\in S}\sum_{s''\in S} Z(o|s'',a)P(s''|s,a)b(s) \ . \tag{5}$$

Analytical Solution

Deriving an analytic solution for particular planning horizons yielded significant insight into the problem. For a single-year planning horizon, there is no time to adjust management effort in light of survey results, so surveying is never optimal. For all other planning horizons, the optimal decision depends on our belief that the species is persisting in the reserve. The analytic solution can be re-arranged to provide a rule of thumb for how many years to manage and survey based on our belief in the persistence of the species and conditional on estimates of detectability, probability of persistence.

In the POMDP solutions, the choice of management strategy changes from "manage", to "survey", and then to "do nothing" as the probability that the species is extant (*b*) declines. Therefore, the solution can be characterised as finding the values of *b* at the two transitions (changing from manage to survey, and then survey to do nothing). The first transition point ($b_{m/s}$) can be approximated by considering a three time-step solution. A three time-step solution is reasonable because this transition value is relatively insensitive to the time horizon (e.g., Fig. 2).

First, we can determine the expected value of managing the species. If b is the current probability that the species is extant, then the probability it will be extant in the next time step if we manage it is $p_m b$, where p_m is the probability the species will remain extant if we manage it. Given that b is close to the boundary between managing and surveying, b will decline such that managing is no longer optimal. Based on the POMDP solutions, we should do nothing in the final two time steps if the value of b is at the boundary between where we should survey and where we should manage. Thus, if we manage the species, the probability that it will be extant after three time steps is $p_0^2 p_m b$, and the net expected value of the species (accounting for annual management costs of c_m) is:

$$\begin{aligned} V_m &= V(p_m b + p_m p_0 b + p_m p_0^2 b) - c_m \\ &= Vbp_m(1 + p_0 + p_0^2) - c_m, \end{aligned}$$

where V is the annual value of the species being extant.

This can be compared to the expected value of the species if we survey. If we survey and see the species, then we know it is alive, providing a value of V (b = 1), and then we assume that we will manage it in the next two years, providing a value of $Vp_m + Vp_m^2$, and incurring a cost of $2c_m$. Thus, the value of the species for the next two years if it is seen will equal

$$\begin{aligned} V_{seen} &= V + Vp_m + Vp_m^2 - 2c_m \\ &= V(1 + p_m + p_m^2) - 2c_m. \end{aligned}$$

If it is not seen in the survey, then the probability of it being extant will decline, depending on the reliability of the survey. Prior to the survey, the probability of it being extant will equal p_0b, where p_0 is the probability that the species remains extant when it is not protected by management. Following the survey, the posterior probability that the species will be extant will equal (using Bayes' rule):

$$b_{post} = \frac{p_0 b(1-d)}{1-p_0 bd},$$

where d is the probability of seeing the species if it is extant (also called detectability). In the second time step, there is no value in surveying, so we assume that we will do nothing in that and the final time step, and the probability that the species is extant will reduce to $p_0^2 b(1-d)/1-p_0bd$ and $p_0^3 b(1-d)/1-p_0bd$. Therefore, the expected value of the species if we do not see it will equal:

$$V_{not\ seen} = V\left(1+p_0+p_0^2\right)\frac{p_0 b(1-d)}{1-p_0 bd}.$$

Finally, the expected value of surveying (V_s) can be obtained by averaging $V_{\text{not seen}}$ and V_{seen} depending on the probability that the species will be seen if we survey (p_0bd), and subtracting the cost of surveying (c_s). Thus,

$$V_s = p_0 bd\left[V\left(1+p_m+p_m{}^2\right)-2c_m\right]+\left(1-p_0 bd\right)[V(1+p_0+p_0{}^2)\frac{p_0 b(1-d)}{1-p_0 bd}] - c_s.$$

The value of $b_{m/s}$ can be obtained by setting $V_m = V_s$, and solving for b. This leads to:

$$b_{m/s} \approx \frac{(c_m - c_s)}{\left[2c_m dp_0 + V(p_m - p_0)(1+(1-d)p_0(1+p_0)-dp_0 p_m)\right]}.$$

The number of years that we should manage a species after last seeing it can be determined by finding the time it takes for the probability that the species is extant to decline from a value of 1 to $b_{m/s}$. After T_m years of protection, the probability that the species is extant will equal $p_m{}^{Tm}$. Therefore, setting $b_{\text{m/s}} = p_m{}^{Tm}$ and solving for T_m leads to

$$T_m = \frac{\log\left(b_{m/s}\right)}{\log\left(p_m\right)}.$$

The value of b for which surveying and doing nothing have equal value ($b_{s/n}$) is sensitive to the timeframe of management, although as the time horizon increases, it approaches an asymptote (Fig. 1). Therefore, we wish to obtain a relatively long-term solution for $b_{s/n}$ that will approximate this asymptote. The expected value of the species if we do nothing for T years is equal to:

$$\begin{aligned} V_n &= V\left(bp_0 + bp_0^{\,2} + bp_0^{\,3} + \cdots + bp_0^{\,T}\right) \\ &= Vbp_0 \frac{1-p_0^{\,T}}{1-p_0} \end{aligned}$$

If we survey and see the species, then the expected value will be V in the first year and then $Vp_m^{\,t}$ in each of the subsequent years as we move to managing it. Therefore, the expected value if it is seen is equal to:

$$\begin{aligned} V_{seen} &= \left(V + Vp_m + Vp_m^{\,2} + \ldots + Vp_m^{\,T-1}\right) - c_m\left(T-1\right) \\ &= \frac{V\left(1-p_m^{\,T}\right)}{1-p_m} - c_m\left(T-1\right) \end{aligned}$$

If it is not seen, then the probability that the species is present will decline to $p_0 b\left(1 - d\right)/\left(1 - p_0 bd\right)$. As we are solving for a value of b that discriminates between surveying and doing nothing, this decline will then move the population into a state for which it is optimal to do nothing. So, for the following T-1 years we will do nothing. Therefore, if the species is not seen, the expected value is:

$$\begin{aligned} V_{notseen} &= \left[\frac{Vp_0 b\left(1-d\right)}{1-p_0 bd}\right]\left(1 + p_0 + p_0^{\,2} + \ldots + p_0^{\,T-1}\right) \\ &= \left[\frac{Vp_0 b\left(1-d\right)}{1-p_0 bd}\right]\left[\frac{1 - p_0^{\,T}}{1-p_0}\right] \end{aligned}$$

Again, the expected value of surveying (V_s) can be obtained by averaging $V_{\text{not seen}}$ and V_{seen} depending on the probability that the species will be seen if we survey (p_0bd), and subtracting the cost of surveying (c_s). Thus,

$$V_s = p_0bd\left[V\frac{1-p_m{}^T}{1-p_m} - c_m\left(T-1\right)\right] + \left(1-p_0bd\right)\left[Vp_0b\frac{1-d}{1-p_0bd}\right]\left[\frac{1-p_0{}^T}{1-p_0}\right] - c_s\,.$$

To determine when the value of surveying is the same as the value of doing nothing, we can solve $V_s = V_n$ for b over an appropriate time horizon T. Ideally we would like T to be as large as possible to approximate the asymptotic result, and to reflect a long-term conservation concern. However, the above analysis is based on assuming that protection continues for T–1 years if the species is seen. This length of time was obtained previously as T_{m}, which then provides the time horizon over which to evaluate $V_s = V_{\text{n}}$. Therefore, using this value for T:

$$b_{s/n} \approx \frac{c_s\left(1-p_m\right)\left(1-p_0\right)}{\left[p_0d\left(V\left(p_m - p_0 + p_0{}^T\left(1-p_m\right) - p_m{}^T\left(1-p_0\right) - c_m\left(1-p_m\right)\left(1-p_0\right)\left(T-1\right)\right)\right)\right]}\,.$$

We can determine the number of years of surveying by evaluating the number of years of absence surveys that are necessary to reduce b from $b_{m/s}$ *to* $b_{s/\text{n}}$. This can be obtained from an iterative evaluation of Bayes' rule. Given b_t in one year, the prior probability for the presence of the species in the next year when we survey is p_0b_t, and if we do not see the species, the posterior probability of presence in time t+1 is $b_{t+1} = p_0b_t\left(1-d\right)/1-p_0b_td$. More generally, it can be shown that if the species is surveyed for T_{s} years and is not seen, the posterior probability for its presence is (obtained by setting $a_t = 1/b_t$, and obtaining an iterative solution for $a_{t+T_{\text{S}}}$ before back-transforming to obtain $b_{t+T_{\text{S}}}$):

$$b_{t+T_s} = \frac{b_t\left(\left(1-d\right)p_0\right)^{T_s}\left(1-\left(1-d\right)p_0\right)}{1-p_0\left(1-d\left(1+b_t\left(\left(\left(1-d\right)p_0\right)^{T_s}-1\right)\right)\right)}.$$

Therefore, given $b_t = b_{m/s}$ (the probability that the species is extant when we start surveying) we can determine the number of years of surveying (T_s) necessary for $b_{t+T_\mathrm{s}} = b_{\mathrm{s/n}}$, which is

$$T_s = \frac{\log\left[b_{s/n}\left(1-p_0\left(1-d\left(1-b_{m/s}\right)\right)\right)/b_{m/s}\left(1-p_0\left(1-d\left(1-b_{s/n}\right)\right)\right)\right]}{\log\left[\left(1-d\right)p_0\right]}.$$

Sumatran Tiger Parameters

Linkie *et al*. (1) undertook repeat surveys of tiger habitat occupancy in the Kerinci Seblat region in order to identify areas of core suitable habitat, the proportion of those habitats that were utilised by the tigers, and the densities of tigers in utilised habitats. Their report provides insights into the reliability of tiger surveys (the average detectability of tigers), as well as identifying the level of poaching protection necessary to maintain tiger populations. From this work and unpublished data on the cost we derived parameter estimates for the cost of implementing management, C_m, cost of surveying, C_s, probabilities of extinction, p_0 and p_m, and detectability, d, for a population of Sumatran tigers in the Kerinci Seblat region.

Linkie *et al*. (1) found that under a range of management scenarios, maintaining poaching levels below 3 tigers per year in core habitats substantially reduced the local extinction probability for the species. We assume if implemented, poaching protection is successful and that poaching was reduced to below three tigers annually. Consequently, assuming successful poaching exclusion in the second largest subpopulation (core population 1) of Sumatran tigers (see Fig. 4a in Linkie *et al*. (1)), we were able to interpolate 0.05816 as the yearly local extinction probability (p_{em}: the probability that the species would go extinct in any given year when managed) and a local survival probability (p_m: the annual probability that the species would remain extant when managed) equal to 0.94184. The probability of local survival for any given year that the species is not protected (p_n) was estimated at 0.9 based on the yearly survival probability of a breeding female Sumatran tiger (taken from Table 1 Linkie *et al.* (1)) and thus the probability of local extinction for any given year that the species is not protected (p_{en}) was estimated at 0.1.

The yearly management cost to implement management to reduce the number of tigers removed via poaching in core population 1 to ≥3 tigers/year was C_m=18,784. The estimate was based on patrol budget data from the Kerinci Seblat area (Linkie unpublished data, Martyr unpublished data). A yearly survey cost was estimated based on surveys covering 10% of this core subpopulation, such that C_s=10,840 (Linkie unpublished data, Martyr unpublished data). Both these costs are based solely on the field costs associated with management and monitoring. We assumed that if a standard sampling strategy was employed, and approximately 30 female tigers remained extant (the minimum sized population worth detecting), the probability that the population would be successfully detected during surveys was 0.78. This figure was based on previous work indicating that the probability of detecting a tiger in any one survey location, given that it utilizes the general area around the survey location is approximately 0.5 (1), and the binomial probability of detecting one tiger at any one of 50 core-habitat survey locations of the possible 500 core habitat locations that could be surveyed.

We assume that the population of the species in our park has a value, *V*. This value was derived from the external donor funding specifically raised for Sumatran tiger conservation in Kerinci Seblat National Park. From 1998-2006, US$1,576,205 was raised for these conservation activities (2).

Other Species Values

The 2007 whooping crane (*Grus Americana*) recovery plan provides sufficient data to evaluate the value of the whooping crane relative to its cost of management (3). The cost of management and surveying for the next 30 years is estimated to be $126 million (3). Survey decisions include conducting aerial surveys to determine total population numbers, movements, territories, habitat use, mortality and movements in migration. The survey activity has a total cost of $5,205,000 for 30 years or $173,500 annually (3). The corresponding cost of management is therefore $4.0265 million. Assuming that the low value of WTP for United States residents is $0.5 billion (3) the ratio V/C_m for the endangered whooping crane is 124.

Although most study on WTP assume contributions of US and European residents, Bandara and Tisdell have evaluated the WTP for the endangered Asian elephants (*Elephas maximus maximus)* through contribution of Sri Lanka's residents only (4). WTP value was sufficient to pay the damages caused by elephants to farmers and V/C_m= 2. This ratio will be significantly different with WTP of non-residents.

The Mexican spotted owl *(Strix occidentalis lucida)* is a charismatic threatened species. According to Loomis *et al*. (5) V/C_m is 450 using WTP of Mexican spotted owl in 1997 ($1.8 billion low value) and the cost of the recovery plan from US Fish & Wildlife Service on average $4 million each year.

The total estimated cost of recovery of the threatened southern sea otters (*Enhydra lutris nereis*) over 20 years is $10,219,700 (6) while Loomis estimated its non-market value to California residents to be $21.4 million for 10 years (7). This brings the V/C_m to 4.18. Similarly the western population of Steller sea lion (*Eumetopias jubatus*) rates 404.26 (C_m= 430,425,000 for 30 years (8) and WTP of US residents $5.8 billion (9)).

Sumatran Tiger WTP

We assume that the population of the species in our park has a value, *V*. This value was derived using contingent valuation methods. While such valuations ignore many things, they are a useful lower bound to local value of a species. A major impediment to the calculation of *V* is the lack of reliable statistics on tourism in the region. The Bukit Lawang Orang-utan centre in the Leuser National Park of northern Sumatra was estimated to accommodate more than 500,000 visitors each year in one study (10), and approximately 10,000 visitors per year in another (11). High-profile tiger reserves in India receive between 100,000 and 400,000 visitors each year, with larger parks generating an income of 20-30 million Rp, not including the adjunct benefits to local communities (Government of India). Van Beukering et al. (2003)(11) conducted a survey of spending patterns and 'willingness to pay' (WTP) for the conservation of the Leuser Ecosystem, to the north of the of the Kerinci Seblat region, resulting in a tourism net present value (NPV) for the Leuser Ecosystem of between US$171-828 million (for the period 2000-2030 at a discount rate of 4%), depending on the future macro-economic policy adopted by the Indonesian government. Policies were grouped broadly into 'deforestation', 'selective-use' and 'conservation'.

We obtained a course estimate of the tiger contribution by dividing this value between the charismatic fauna groups largely responsible for attracting tourism to the area. These broad groups include the tiger, the Sumatran Rhinoceros, the Orang-utan and a range of other primates, other mammals such as the sun bear and clouded leopard, and numerous endemic and near-endemic birds. Extrapolating from the valuation of van Beukering et al. (2003)(11), we ascribe a 30 year NPV to tiger existence in the region of US$150 million, or alternatively, a cost of US$150 million for failure to maintain a viable population of tigers. One of the major assumptions of this approach is that the values ascribed to wildlife tourism are equal across broad species groups and additive (and substitutable).

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