Appendix B. Including imperfect monitoring and Type I and Type II errors in the derivation of the two principles.

When monitoring is not perfect, there are Type I and Type II errors, $\alpha(n)$ and $\beta(n)$, which are dependent on the number of monitoring surveys (more monitoring will reduce the error rates). They are also dependent on a number of factors related to the efficiency of monitoring, such as species' detectability (Garrad et al. 2012, Wintle et al. 2013). We can analyse the system in exactly the same way as in the main text.

Monitor a species i for which we already planning to take management action. There are four possibilities:

- with probability δ_i, species *i* is in decline, probability detected = $(1-\beta_i(n_i))$, and $\Delta U = -\delta_b M_i / C_b$.
- with probability δ_i, species *i* is in decline, probability not detected = $\beta_i(n_i)$, and $\Delta U = (-1+\delta_b (C_i - M_i) / C_b$.
- with probability $1-\delta_i$, species *i* is not in decline, probability no decline detected = $(1-\alpha_i(n_i))$, and $\Delta U = \delta_b (C_i - M_i) / C_b$.
- with probability $(1 - \delta_i)$, species *i* is not in decline, probability decline falsely detected = $\alpha_i(n_i)$, and change in $U = -\delta_b M_i / C_b$.

Hence, the expected reduction in the number of species declining is:

$$E[-\Delta U] = \delta_i \left[-\frac{\delta_b M_i}{R_b}(1-\beta_i(n_i) + \beta_i(n_i)(-1+\frac{\delta_b(R_i - M_i)}{R_b}\right] + (1 - \delta_i)\left[(1-\alpha_i(n_i))\delta_b\frac{(R_i - M_i)}{R_b} + \alpha_i(n_i)(-\frac{\delta_b M_i}{R_b})\right]$$

$$E[-\Delta U] = \delta_b \left[\frac{R_i}{R_b}(1-\delta_i)(1-\alpha_i(n_i)) - \frac{M_i}{R_b} - \beta_i(n_i)\delta_i(\frac{1}{\delta_b} - \frac{R_i}{R_b})\right] \quad \text{(B.1)}$$

The same as eqn 3 in the main text, except with the extra terms for $\alpha_i(n_i)$ and $\beta_i(n_i)$. As before, this has a maximum when C_i is large and δ_i is small; i.e. a species on the boundary. In which case $\delta_i = \delta_b$ and $C_i = C_b$, and:

$$E[-\Delta U] = \delta_b((1-\delta_b)(1-(\alpha_i(n_i)+\beta_i(n_i))) - \frac{M_i}{R_b}) \quad \text{(B.2)}$$

The same as eqn 4 in the main text, except with the extra terms for $\alpha_i(n_i)$ and $\beta_i(n_i)$.

Monitor a species i for which we planning to not take management action. There are four possibilities:

- with probability δ_i, species *i* is in decline, probability detected = $(1-\beta_i(n_i))$, and $\Delta U = 1-\delta_b(C_i+M_i) / C_b$.
- with probability δ_i, species *i* is in decline, probability not detected = $\beta_i(n_i)$, and $\Delta U = -\delta_b M_i / C_b$.
- with probability $1-\delta_i$, species *i* is not in decline, probability no decline detected = $(1-\alpha_i(n_i))$, and $\Delta U = -\delta_b M_i / C_b$.
- with probability $(1 - \delta_i)$, species *i* is not in decline, probability decline falsely detected = $\alpha_i(n_i)$, and change in U $= -\delta_b(C_i+M_i) / C_b$.

Hence, the expected reduction in the number of species declining is:

$$E[-\Delta U] = \delta_i \left[\left(1-\beta_i(n_i)\right)\left(-\delta_b \frac{M_i}{R_b}\right) + \beta_i(n_i)\left(-1+\delta_b \frac{(R_i - M_i)}{R_b}\right)\right] +$$

$$(1-\delta_i)\left[(1-\alpha_i(n_i))\delta_b\frac{(R_i-M_i)}{R_b}-\alpha_i(n_i)\delta_b\frac{M_i}{R_b}\right]$$

$$E[-\Delta U]=\delta_b\left[\delta_i\left(\frac{1}{\delta_b}-\frac{R_i}{R_b}\right)(1-\beta_i(n_i))-\frac{M_i}{R_b}-\alpha_i(n_i)(1-\delta_i)\frac{R_i}{R_b}\right] \quad \text{(B.3)}$$

This has a maximum when C_i is small and δ_i is large; i.e. a species on the boundary again. In which case $\delta_i = \delta_b$ and $C_i = C_b$, and:

$$E[-\Delta U]= \delta_b\left[(1-\delta_b)(1-(\alpha_i(n_i)+\beta_i(n_i)))-\frac{M_i}{R_b}\right] \quad \text{(B.4)}$$

exactly the same as before. So in all cases again, the best species to monitor are ones on the boundary of taking action.

The Type I and Type II errors, $\alpha(n)$ and $\beta(n)$, are dependent on the number of monitoring surveys (more monitoring will reduce the error rates). Analysing the system in exactly the same way as above for species which we are already planning to take management action, the expected reduction in the number of species declining with an increase in monitoring is:

$$\frac{dE[-\Delta U]}{dn_i}=\delta_b\left[\frac{C_i}{C_b}(1-\delta_i)\left(-\frac{d\alpha(n_i)}{dn_i}\right)-\frac{M_i}{C_b}-\frac{d\beta(n_i)}{dn_i}\delta_i\left(\frac{1}{\delta_b}-\frac{C_i}{C_b}\right)\right] \quad \text{(B.5)}$$

where n_i is the number of surveys for species *i*. The terms $d\alpha(n_i)/dn$ and $d\beta(n_i)/dn$, are the rate of change of Type I and Type II errors as the amount of monitoring increases. These will be negative functions, i.e. the proportion of errors decreases as monitoring increases, and tends to zero as the survey effort increases, so that there is a diminishing rate of return from more surveys (or a decreasing gain in information as the survey effort increases).

The error rates, $\alpha(n)$ and $\beta(n)$, are functionally related to one another via the choice of a common statistical threshold; increasing the likelihood of detecting a true decline will also mean a higher likelihood of falsely detecting a decline when no effect is occurring (Field et al. 2004). If the expected cost of missed detections (Type II errors) is greater than the expected cost of false alarms (Type I errors) (e.g. for valuable species), then the optimum statistical threshold will be set such that the probability of a missed detection of a true decline is close to zero (i.e. β will always be close to 0, and the power 1-β close to 1). The greater the difference between the expected cost of missed detections and the expected cost of false alarms, the closer β will be to 0. As the amount of monitoring effort increases, the optimal statistical threshold will change so as to also decrease the amount of false alarms (α), but β will always be close to 0. Consequently, $d\beta(n) / dn \approx 0$, and the change in the utility function with an increase in the monitoring is:

$$\frac{dE[-\Delta U]}{dn_i} = \delta_b \left[\frac{C_i}{C_b}(1-\delta_i)\left(-\frac{d\alpha(n_i)}{dn_i}\right) - \frac{M_i}{C_b}\right] \qquad \text{(B.6)}$$

This result is the same as in the main text (eqn 3), except in the main text monitoring was perfect so that $d\alpha / dn$ = -1. In this case, how quickly the error rate decreases with monitoring is an additional factor in determining whether monitoring is cost-effective. Generally, more variable populations will mean that the error rates decrease more slowly with time and the benefit is therefore less. In general, imperfect monitoring does not qualitatively affect any of the results; there is simply one additional term for how quickly monitoring reduces errors.

Literature Cited

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