

Species existence value and implications for investments in habitat enhancement: a real options approach

Abstract

We build a real options model to investigate when it is worthwhile investing in costly measures which enhance the habitat for a species in a particular area and thus increase the species viability. To this end we quantify the existence value of a species as the discounted value of a constant flow of benefits received as long as that species continues to survive within a particular area of interest and determine the change in that value if habitat enhancement measures are taken. We also investigate whether increased climatic variability make these measures more valuable, in terms of enhancing existence value.

Using a model which incorporates stochastic logistic growth in population size, Allee effects (where due to additional co-operation/protection/mating opportunities there is positive density dependence in the mean growth rate for intermediate population densities) and potential immigration, we find that increased environmental stochasticity, for example due to increased temperature variability, increases the probability of extinction and thus decreases existence values for a given population size, but also increases the effectiveness of habitat enhancement measures. So, particularly when species are close to extinction, higher risk due to climatic variation makes it more worthwhile to invest in habitat enhancement measures which reduce the likelihood of extinction, and to do so over a wider range of population sizes.

In future work we will consider two habitat patches, subject to imperfectly correlated environmental variability, in order to investigate factors which influence the marginal benefits of an additional habitat patch and of patch connectivity.

1 Extended abstract

Whilst most economic models valuing biodiversity (*e.g.* Kassar & Lasserre (2004)) have focussed on the benefits in terms of the provisioning, regulating or supporting ecosystem services biodiversity provides, many willingness-to-pay studies report results consistent with existence value representing an important component of the value placed on species for some individuals (see for example Jacobsen, Lundhede & Thorsen (2012)). Existence value represents the benefit received simply from knowing the species exists.

In this paper we use real option techniques to model the existence value for a species as the discounted value of a constant flow of benefits received as long as that species continues to survive within a particular area of interest. This could be at a national scale, or, particularly if incorporating a *warm glow* effect where proximity to the species matters for existence value, on a more local level. We focus on potentially endangered species and thus assume habitat suitable for the species occurs only within a specific patch or patches within the region of interest.

Our aim is to investigate when it is worthwhile, simply on the basis of a species' existence value, investing in costly measures which either enhance the habitat in a particular patch (and thus increase the species mean population growth rate within the patch), or increase immigration levels from neighbouring patches, for example by increasing connectivity between patches. Furthermore, does increased climatic variability make these measures more valuable (in terms of enhancing existence value)?

We start by considering a single patch of habitat suitable for the particular species and assume a constant flow of benefits b_e arises as long as the species continues to survive. If extinction were impossible, the species existence value would thus be b_e/ρ where ρ is the risk-free rate of interest. More generally, the flow of benefits arises only whilst the species survives within the patch, so the existence value of a species within the habitat patch i is given by

$$V_e^i(N_i) = E \left[\int_0^{\tau_e} b_e e^{-\rho t} dt \right] < \frac{b_e}{\rho}$$

where τ_e is the first time the population size within the patch (N_i) falls to zero.

The species existence value depends on the evolution of the population of the species within the habitat patch over time. Following the conservation/invasion biology literature (Lewis, Petrovskii & Potts (2016)) we assume the size of the population within patch i , N_i evolves according to

$$dN_i = \left(r_i N_i \left(1 - \frac{N_i}{k_i} \right) - \lambda \theta \frac{N_i}{\theta + N_i} + p_i \right) dt + [\sigma_2^2 N_i^2 + \sigma_1^2 N_i + \sigma_0^2]^{\frac{1}{2}} dW \quad (1)$$

The first term in the deterministic component represents logistic mean growth in population size. Here r_i represents the mean growth rate in the absence of density-dependent constraints and is determined by species characteristics but also by the suitability of the habitat for that species. The logistic function implies a decreasing growth rate for high population densities close to the carrying capacity of the patch, k_i . The second term captures Allee effects (as in Drake & Lodge (2006)), i.e. decreased population growth rates at low densities due to limitations in potential mating opportunities when the population density is low. Here θ captures limitation of mates and λ the consequent reduction in the birth rate. Allee effects give rise to positive density dependence in the mean growth rate for intermediate population densities. Finally the third term, p_i represents net immigration of the species to/from patch i . The stochastic component captures variability from environmental, demographic and immigration sources (as in Potapov & Rajakaruna (2013)).

The species existence value in the absence of any habitat enhancement thus satisfies the HJB equation

$$(\sigma_2^2 N_i^2 + \sigma_1^2 N_i + \sigma_0^2) \frac{\partial^2 V_e^i}{\partial N_i^2} + \left(r_i N_i \left(1 - \frac{N_i}{k_i} \right) - \lambda \theta \frac{N_i}{\theta + N_i} + p_i \right) \frac{\partial V_e^i}{\partial N_i} - \rho V_e^i + b_e = 0$$

subject to $V_e^i(0) = 0$ and $\lim_{N_i \rightarrow \infty} V_e^i = \frac{b_e}{\rho}$.

Our preliminary results, which consider a single patch of habitat with exogenous immigration levels, are that increased environmental stochasticity, for example due to increased temperature variability, increases the probability of extinction and thus decreases existence values for a given population size. The impact of such increases in risk is exacerbated by

other factors which reduce the viability of low population sizes, such as Allee effects and when external immigration into the habitat patch is low.

Our goal is to determine when it is worthwhile paying to preserve or enhance habitat for the species. Measures which increase either expected population growth rates within the patch of habitat, r_i , the carrying capacity of the patch, k_i , or immigration into the habitat patch, p_i , all reduce the probability of extinction and thus increase existence value. However, these measures are costly and so will be implemented only if the resulting increase in existence value outweighs the cost.

We assume the habitat-enhancing measures can be started and stopped at any time. The measures incur a fixed cost C_j to initiate and also incur ongoing costs of c_j (for $j = r, k, p$) whilst in operation, but, whilst in operation result in an increase in either $r_i \rightarrow r'_i$, $k_i \rightarrow k'_i$ and $p_i \rightarrow p'_i$. There are thus two possible states of the world: one where the measures are not currently in place but there is the option to start them, and the other where the measures are currently ongoing and there is the option to temporarily suspend them. We write $W_e^i(N)$ for the existence value net of future enhancement costs when habitat-enhancing measures are currently in place, and $V_e^i(N)$ for the value when they are not in place. We then determine the range of population sizes within the patch for which it is worthwhile investing in habitat improvement by solving for the population levels N_I^\pm at which it is worthwhile initiating habitat enhancement, and the population levels at which enhancement should be suspended because it is not currently worthwhile, N_S^\pm .¹ These satisfy the value matching and smooth pasting conditions associated with the two decisions (initiating and suspending measures):

$$\begin{aligned} V_e^i(N_I^\pm) &= W_e^i(N_I^\pm) - C_j \\ \frac{\partial V_e^i}{\partial N_i} \Big|_{N_I^\pm} &= \frac{\partial W_e^i}{\partial N_i} \Big|_{N_I^\pm} \\ W_e^i(N_S^\pm) &= V_e^i(N_S^\pm) \\ \frac{\partial W_e^i}{\partial N_i} \Big|_{N_S^\pm} &= \frac{\partial V_e^i}{\partial N_i} \Big|_{N_S^\pm} \end{aligned}$$

¹We allow for the possibility that habitat enhancement may no longer be cost effective if the population is very large as well as if it is very small, which results in two initiation and two suspension thresholds.

where the value functions $W_e^i(N)$ and $V_e^i(N)$ satisfy (in the case of r enhancement):

$$\begin{aligned} (\sigma_2^2 N_i^2 + \sigma_1^2 N_i + \sigma_0^2) \frac{\partial^2 W_e^i}{\partial N_i^2} + \left(r_i' N_i \left(1 - \frac{N_i}{k_i} \right) - \lambda \theta \frac{N_i}{\theta + N_i} + p_i \right) \frac{\partial W_e^i}{\partial N_i} - \rho W_e^i + b_e - c_r &= 0 \\ (\sigma_2^2 N_i^2 + \sigma_1^2 N_i + \sigma_0^2) \frac{\partial^2 V_e^i}{\partial N_i^2} + \left(r_i N_i \left(1 - \frac{N_i}{k_i} \right) - \lambda \theta \frac{N_i}{\theta + N_i} + p_i \right) \frac{\partial V_e^i}{\partial N_i} - \rho V_e^i + b_e &= 0 \end{aligned}$$

subject to $V_e^i(0) = W_e^i(0) = 0$ and $\lim_{N_i \rightarrow \infty} V_e^i = \lim_{N_i \rightarrow \infty} W_e^i = \frac{b_e}{\rho}$ as applicable.

We find there is generally a range of population sizes (N_I^-, N_I^+) , within which it is worthwhile starting habitat enhancement measures; when the population size is sufficiently small or sufficiently large the difference in existence values does not outweigh the cost (since both existence values equal zero at $N = 0$ and for high N , both are close to the no-extinction upper bound, b_e/ρ , which does not vary with N). Similarly, once habitat enhancement has commenced, it may also be the case, depending on parameter values, that for very low or very high population sizes, the costs of habitat enhancement outweigh the benefits and it is worthwhile suspending the measures. This occurs if $N_i > N_S^+ (\geq N_I^+)$ or $N_i < N_S^- (\leq N_I^-)$.

The range of population sizes for which habitat enhancement should occur depends on the benefit, measured by the increase in existence value relative to the overall cost and is thus larger if the costs of the measures are lower and if the increase in existence value is higher. In preliminary work, we find habitat enhancement measures generally have a greater effect on existence values when climatic variation is high. So, particularly when species are close to extinction, higher risk due to climatic variation makes it *more worthwhile* to invest in measures which reduce the likelihood of extinction, either by enhancing the particular habitat or by promoting immigration, and to do so over a wider range of population sizes.

In further work we plan to extend the model to consider two habitat patches, both subject to environmental variability, but where the environmental risks associated with each patch are not perfectly correlated, for example because their different locations give rise to different exposures to climate change. This will enable us to investigate factors which influence the marginal benefit of an additional habitat patch, both when the two patches are completely isolated from each other and also for different levels of connectivity to the initial patch. It will also provide a means of quantifying the benefits of (additional) patch connec-

tivity, and investigating how the geographical location and connectivity to other patches of similar habitat affect the value of either an existing habitat patch or a potential location for habitat restoration.

Although existence values are calculated for a single species, these can in principle be combined to produce an existence value for all species associated with a particular habitat patch. Furthermore, a species' existence value should in practice be combined with the value of other ecosystem services provided by the species to evaluate decisions over habitat-enhancing investments. However, even if a particular species does not provide any provisioning, regulating or supporting ecosystem services, our results show the resulting increase in a species' existence value alone could motivate such investments, particularly if climate change results in increased population size variability.

References

- Drake JM and Lodge DM (2006). Allee effects, propagule pressure and the probability of establishment: risk analysis for biological invasions. *Biological Invasions* 8: 365-375
- Jacobsen JB, Lunnhede TH and Thorsen BJ (2012). Valuation of wildlife populations above survival. *Biological Conservation* 21: 543-563
- Kassar I and Lasserre P (2004) Species preservation and biodiversity value: a real options approach. *Journal of Environmental Economics and Management* 48: 857-879
- Lewis MA, Petrovskii SV and Potts JR (2016) *The Mathematics behind Biological Invasions*. *Interdisciplinary Applied Mathematics Volume 44*, Springer
- Potapov A and Rajakaruna H (2013) Allee threshold and stochasticity in biological invasions: Colonization time at low propagule pressure. *Journal of Theoretical Biology* 337: 1-14