Land use and habitat conservation under uncertainty

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Background/Motivation

- Decisions about land conservation often require estimates of the value of the ecosystem services provided by the land in the conserved state:
  - Use values
    - provisioning services,
    - regulating services
  - ...but also *non-use* values

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- *Existence value* represents the benefit received simply from knowing the species exists.
  - Evidence from willingness-to-pay studies (*e.g.* Jacobsen, Lundhede & Thorsen (2012)) consistent with *existence value* representing an important component of species value.

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  - Evidence from willingness-to-pay studies (*e.g.* Jacobsen, Lundhede & Thorsen (2012)) consistent with *existence value* representing an important component of species value.
- Consider existence values in a real options setting:
  - impact on incentives to incur costly habitat enhancement measures
  - impact of (climate) variability on existence values and the incentives for habitat enhancement they provide

and how results generalise

Existence Values

- Single patch of habitat
- Continuous constant flow of benefits b_e arises as long as the species continues to survive
- If extinction were impossible, the species existence value would be

$$\frac{b_e}{\phi}$$

where ϕ is the discount rate

Existence Values

- Single patch of habitat
- Continuous constant flow of benefits b_e arises as long as the species continues to survive
- If extinction were impossible, the species existence value would be b_e/ϕ where ϕ is the discount rate
- 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

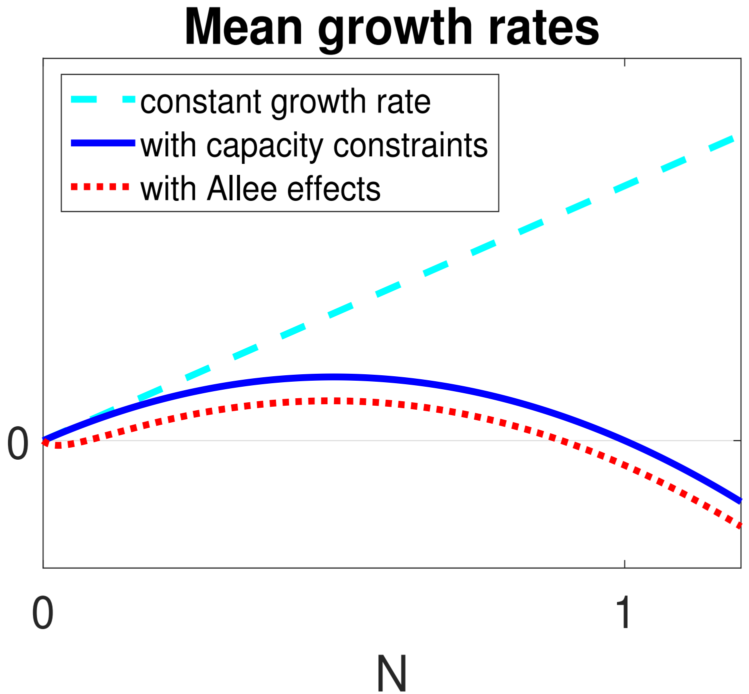
$$V_e^i(N_i) = E\left[\int_0^{\tau_e} b_e e^{-\phi t} dt\right] < \frac{b_e}{\phi}$$

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

Population size evolution

The size of the population within patch i, N_i evolves according to

$$dN_i = \left(r_i N_i \left(1 - \frac{N_i}{k_i}\right) - \lambda\theta \frac{N_i}{\theta + N_i} \right) dt + \left[\sigma_e^2(N_i) + \sigma_d^2(N_i)\right]^{\frac{1}{2}} dW$$



Population size evolution

Evolution of the size of the population within patch i, N_i incorporates

$$dN_i \quad = \quad r_i N_i \left(1 - \frac{N_i}{k_i}\right) dt + \ldots$$

1. logistic mean growth rate in population size:
   - r_i represents the mean growth rate in the absence of density-dependent constraints
     - determined by species characteristics and suitability of habitat
   - k_i represents the carrying capacity of the patch
     - competition for resources for high population densities implies a decreasing growth rate for densities close to k_i.

Population size evolution

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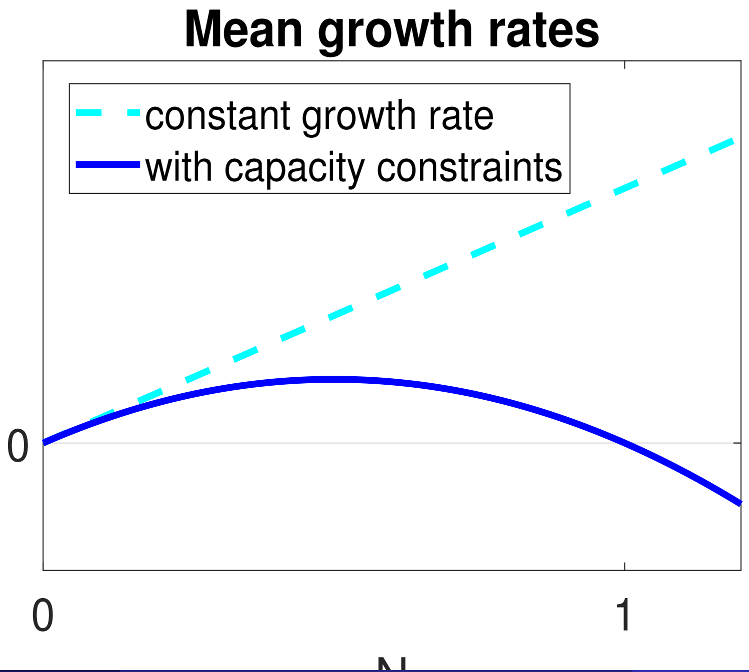

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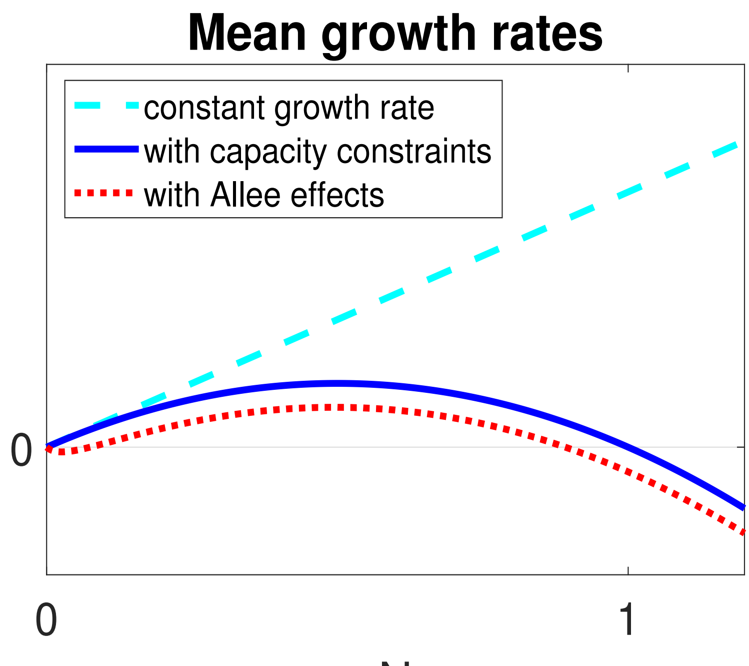
1. logistic mean growth rate in population size:
2. Allee effects, i.e. decreased population growth rates at low densities due to, for example, limitations in potential mating opportunities when the population density is low,
   - θ captures the limitation of mates
   - λ captures the consequent reduction in the birth rate
3. variability from environmental and demographic sources.

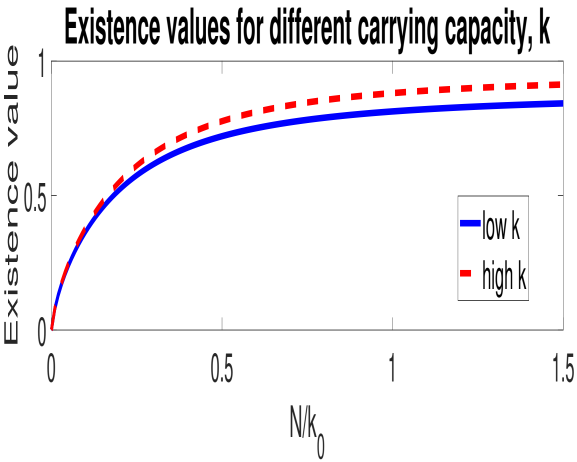
Population size evolution

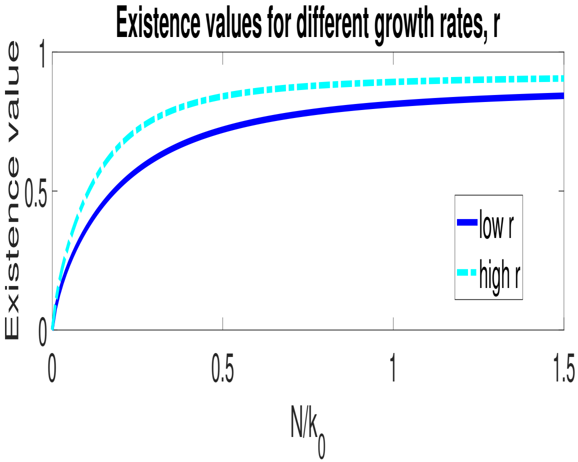
Evolution of the size of the population within patch i, N_i incorporates capacity constraints and Allee effects :

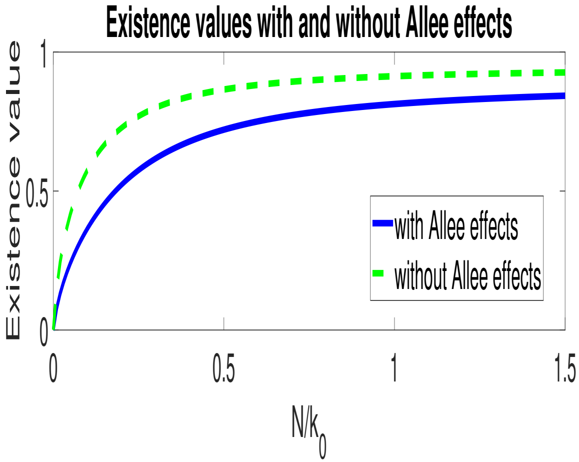
$$dN_i \quad = \quad \left(r_i N_i \left(1 - \frac{N_i}{k_i} \right) - \lambda\theta \frac{N_i}{\theta + N_i} \right) dt + \left[\sigma_e^2(N_i) + \sigma_d^2(N_i) \right]^{\frac{1}{2}} dW$$



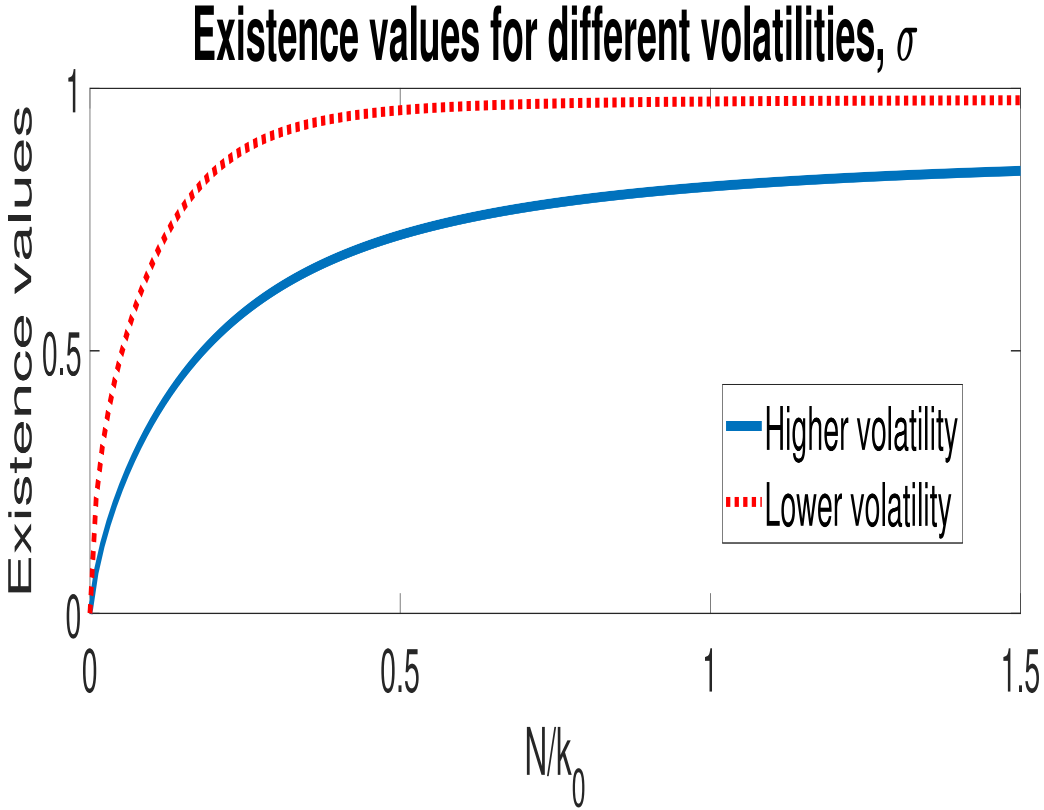
Existence values







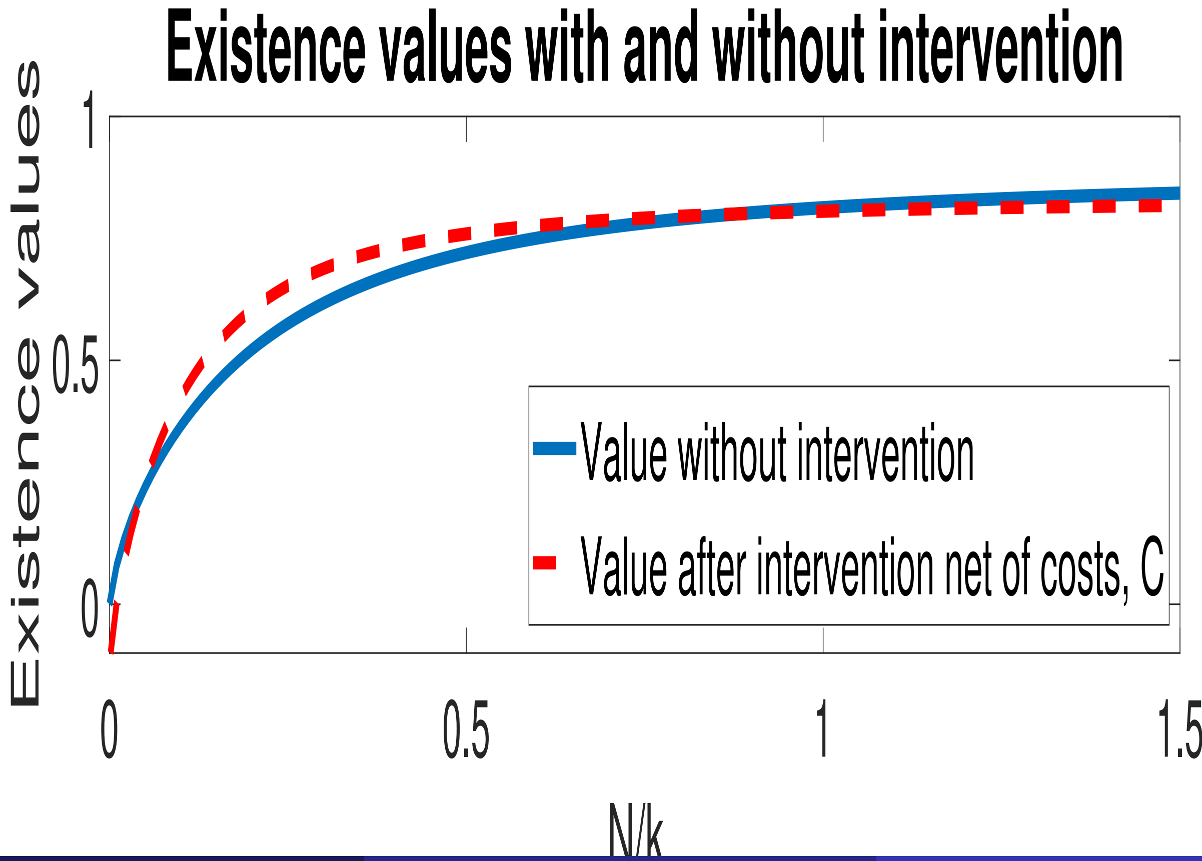
Impact of uncertainty on existence values



Habitat enhancement

- Relative to pristine habitat, degraded habitat
  - will support a smaller species population before competitive pressures reduce the growth rate than pristine habitat,
  - *i.e.* the current carrying capacity of a degraded patch is lower than the theoretical maximum for land of the same area.
- Habitat enhancement measures
  - increase carrying capacity of patch, $k_i \rightarrow K_i = w_k \times k_i$ with $w_k > 1$.
  - incur costs: a one-off up-front cost of C.
- Habitat enhancement is only worthwhile if the benefits exceed the costs
  - benefits measured as the increase in the species existence value, which varies with the population size, N,

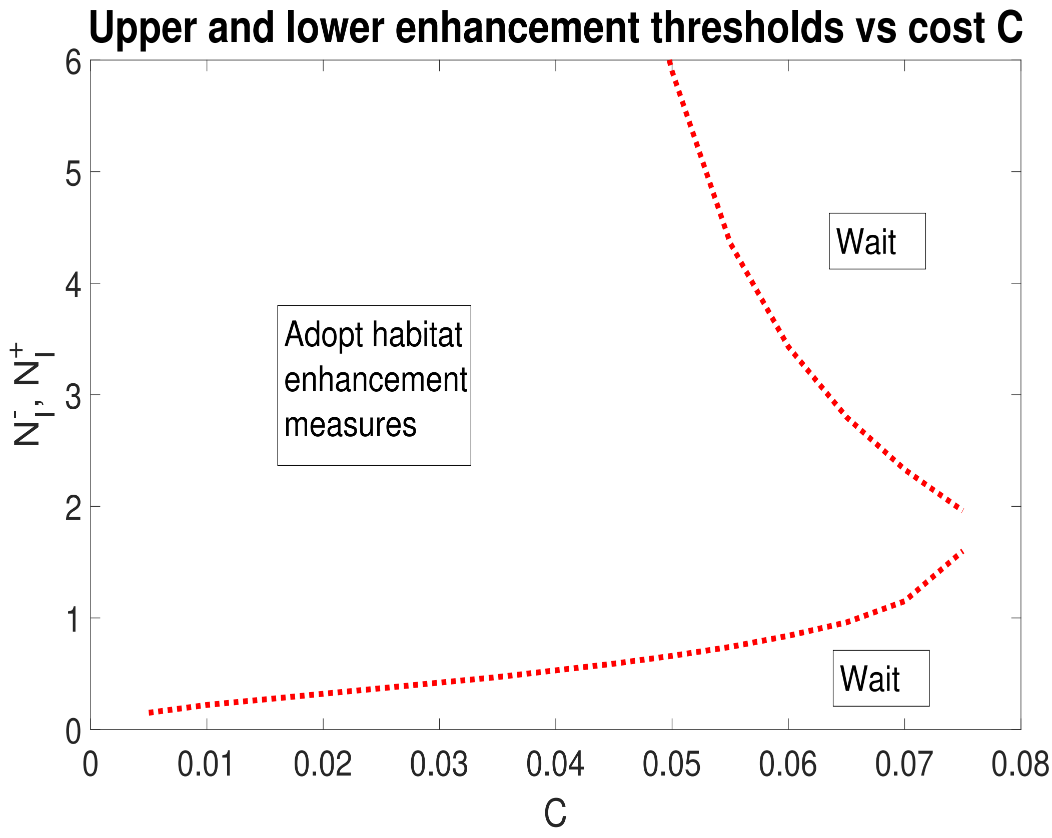
Stylised graph of existence values with and without enhancement net of costs



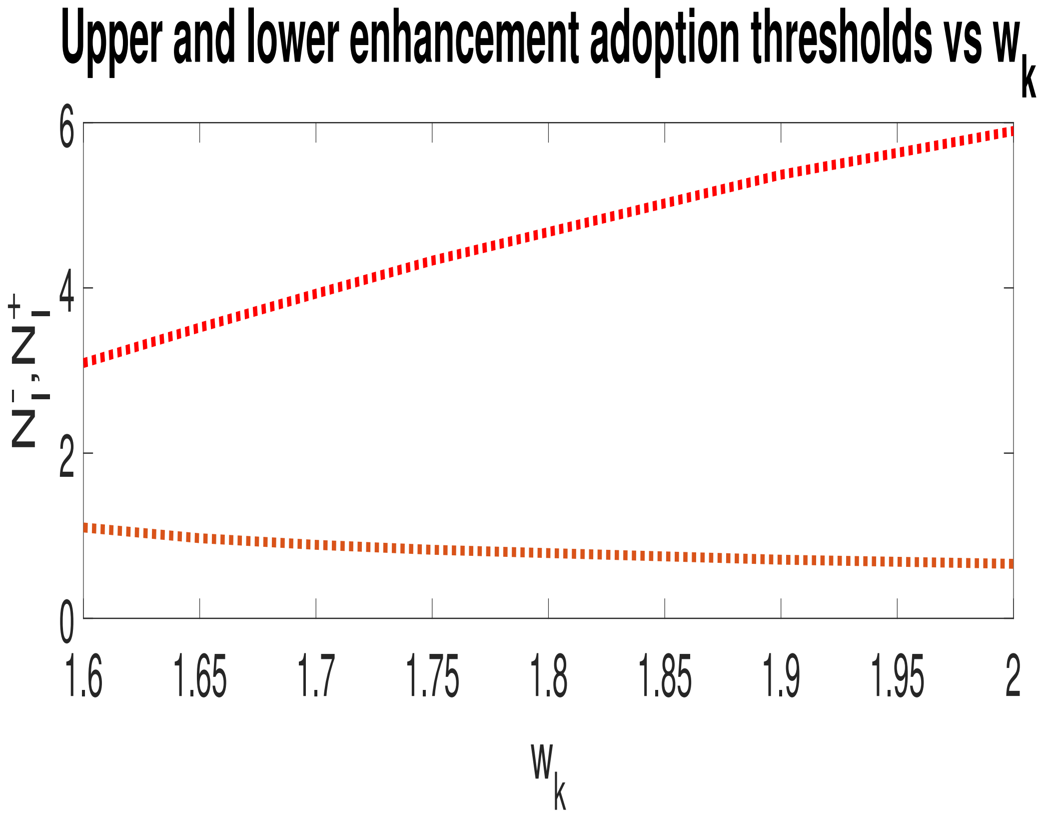
Enhancement strategy

- There are three possibilities, depending on the magnitude of the costs (in order of increasing costs)
  1. Habitat improvement is worthwhile as long as the population size is not too low, *i.e.* $N_I^- < N$
     - if the population is too close to extinction, the benefits do not outweigh the costs
  2. Habitat improvement is worthwhile as long as the population size is in an **enhancement region** *i.e.* $N_I^- < N < N_I^+$
     - if the population is too low or too high, the benefits do not outweigh the costs
  3. Habitat enhancement is never worthwhile
     - the costs always outweigh the benefits
- Solution method
  - Future evolution of the population size is stochastic, so use real options methods to find optimal enhancement region, N_I^- and N_I^+.

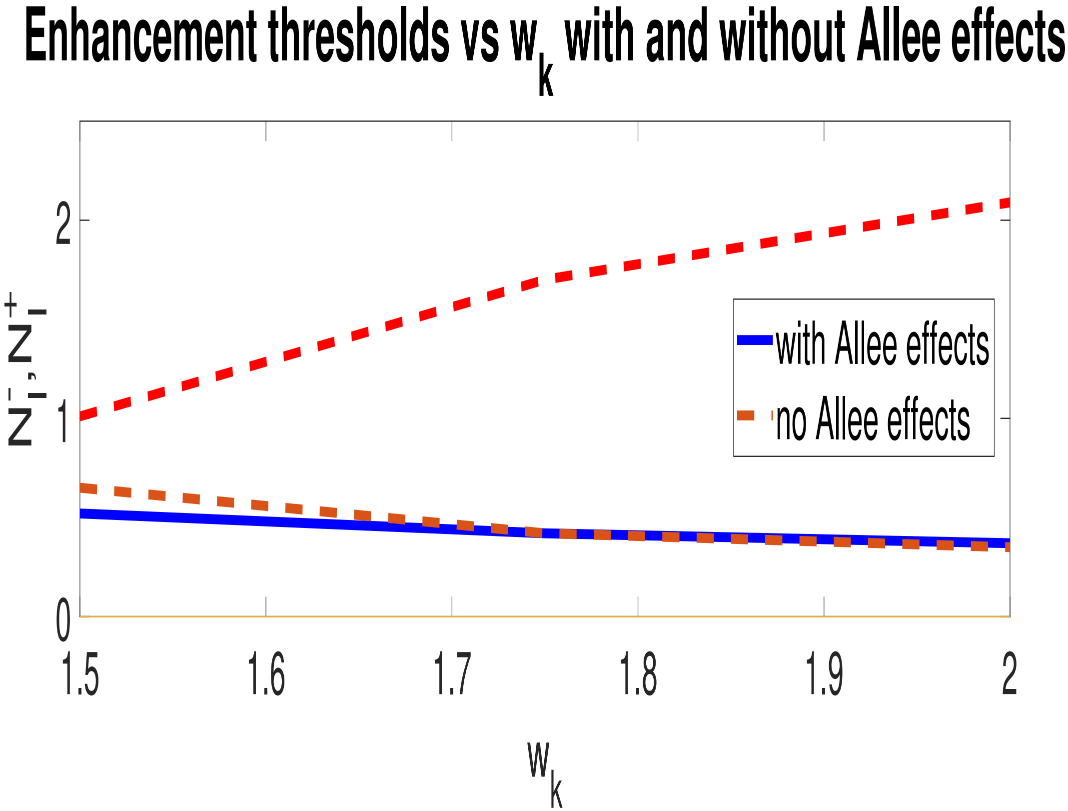
Enhancement thresholds for different costs of enhancement



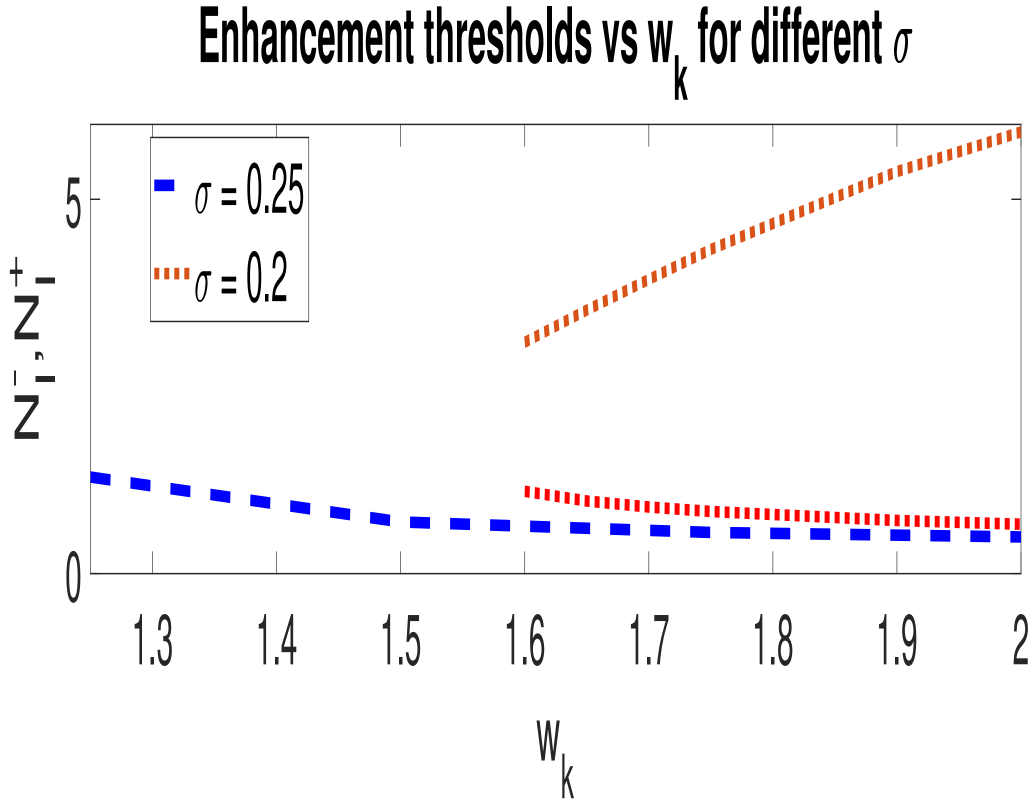
Enhancement thresholds for different levels of habitat enhancement



Impact of Allee effects on enhancement thresholds



Impact of variability on engagement thresholds



Summary of results for species existence model

- Undertaking measures which enhance habitat (increase carrying capacity) are worthwhile because of the increase in existence value if the population size, N, is within an **enhancement region**, which is larger:
    - the greater the increase in carrying capacity
    - the lower the cost
    - if Allee effects are present
    - the greater the environmental variability

Impact of variability

In species existence model, **higher risk** due to climatic variation

- **decreases** existence values, but
- **brings forward** optimal investment in habitat enhancement

This is in contrast to many "standard" real options models of investment, where **higher volatility**

- **increases** option values, and
- **delays** optimal investment

Impact of variability

In species existence model, **higher risk** due to climatic variation

- **decreases** existence values, but
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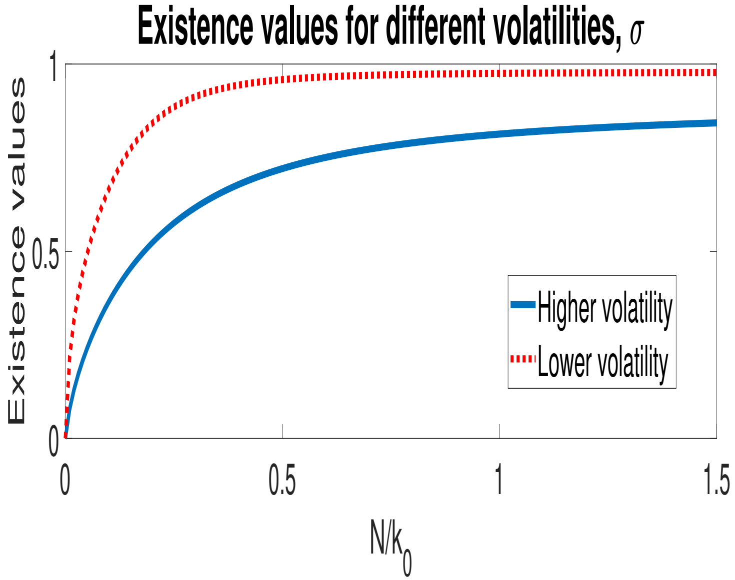
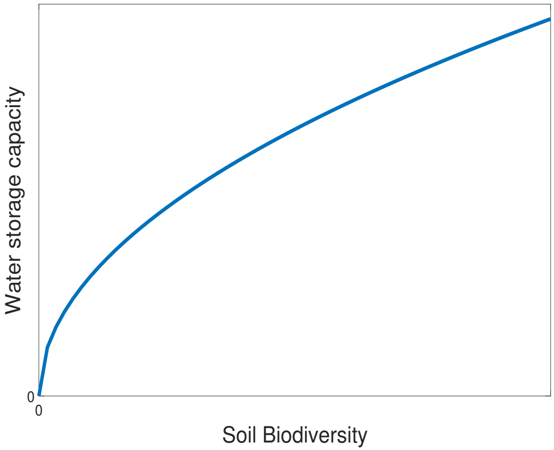
This is because of the **concave** shape of the existence value function:



Concave value functions

- Concave functions are characteristic of many environmental issues
  - Sidibe et al (2018) following Allison (1973) and Bastardie et al (2005) suggest soil water storage capacity S_C is a concave function of soil biodiversity B:

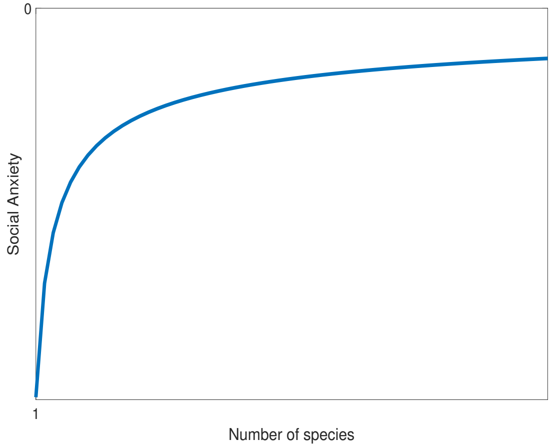
$$S_C = LB^{\mu}; \qquad 0 < \mu < 1$$



Concave value functions

- Concave functions are characteristic of many environmental issues
  - Conrad (2018) / Xu (2021) suggest Social Anxiety function related to species loss:

$$A(N) = -RN^{-\gamma}; \qquad \gamma > 0$$



Concave value functions

- Concave functions are characteristic of many environmental issues
  - Soil water storage capacity S_C as a function of soil biodiversity B:

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  - Conrad (2018)'s Social Anxiety function related to species loss:

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- This is in contrast to many industrial settings, where the payoff to investment is often assumed to be linear

$$\Pi X - K$$

Conrad (2018) / Xu (2021)

Model:

- Social Anxiety function measures "society's concern over declining abundance of a single endangered species" as a flow:

$$A(N) = -RN^{-\gamma}$$

- Species abundance within a single patch N follows GBM
- Costly habitat enhancement measures can reduce volatility and increase growth rate

Results:

- Habitat enhancement measures which reduce volatility and increase growth rate can be worthwhile when N is within an enhancement region

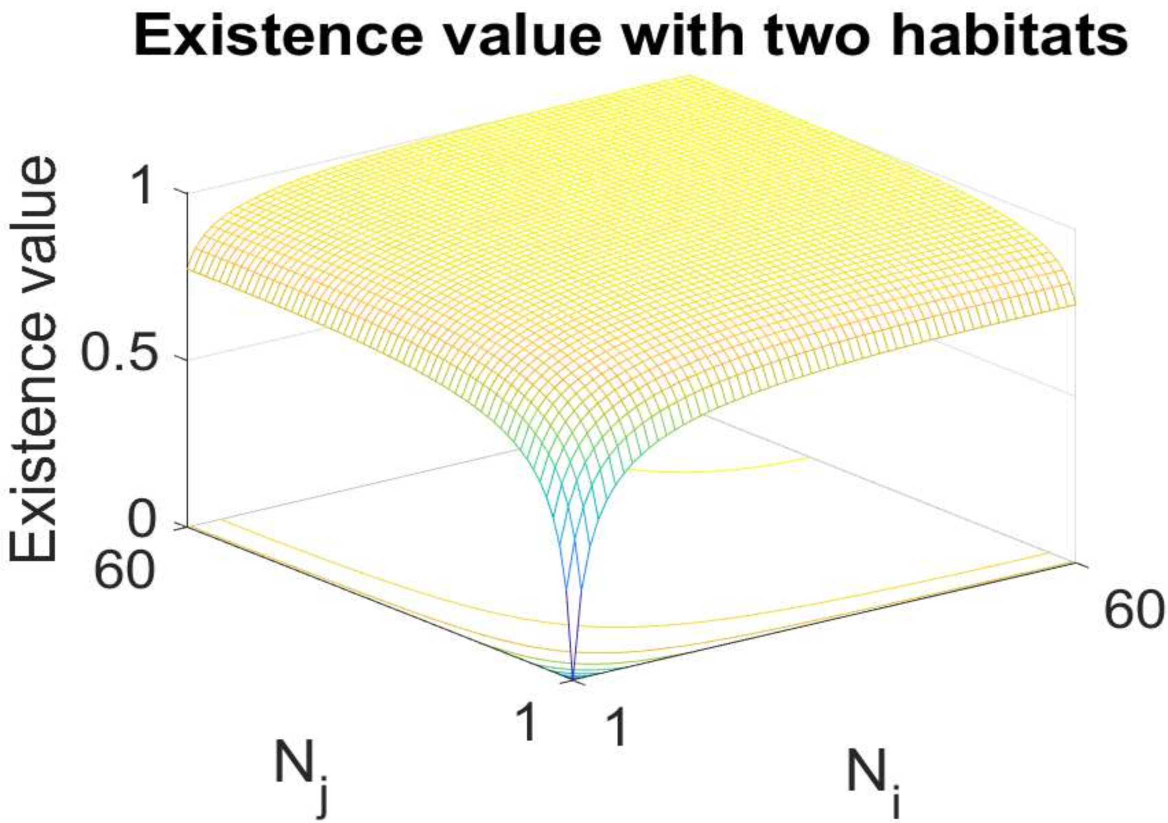
Multiple patch model

- Two patches of land, i and j with population sizes within each patch N_i, N_j.
- Assume flow of benefits as long as species is present globally and additional benefit as long as species is present locally within each patch:

$$b(N) = b_g(1 - (N_i + N_j)^{-\gamma}) + b_i(1 - N_i^{-\gamma}) + b_j(1 - N_j^{-\gamma})$$

- Species abundances N_i, N_j follow GBM with correlation ρ
- Question: What determines the value of an additional patch of habitat?

Multiple patch model - Results



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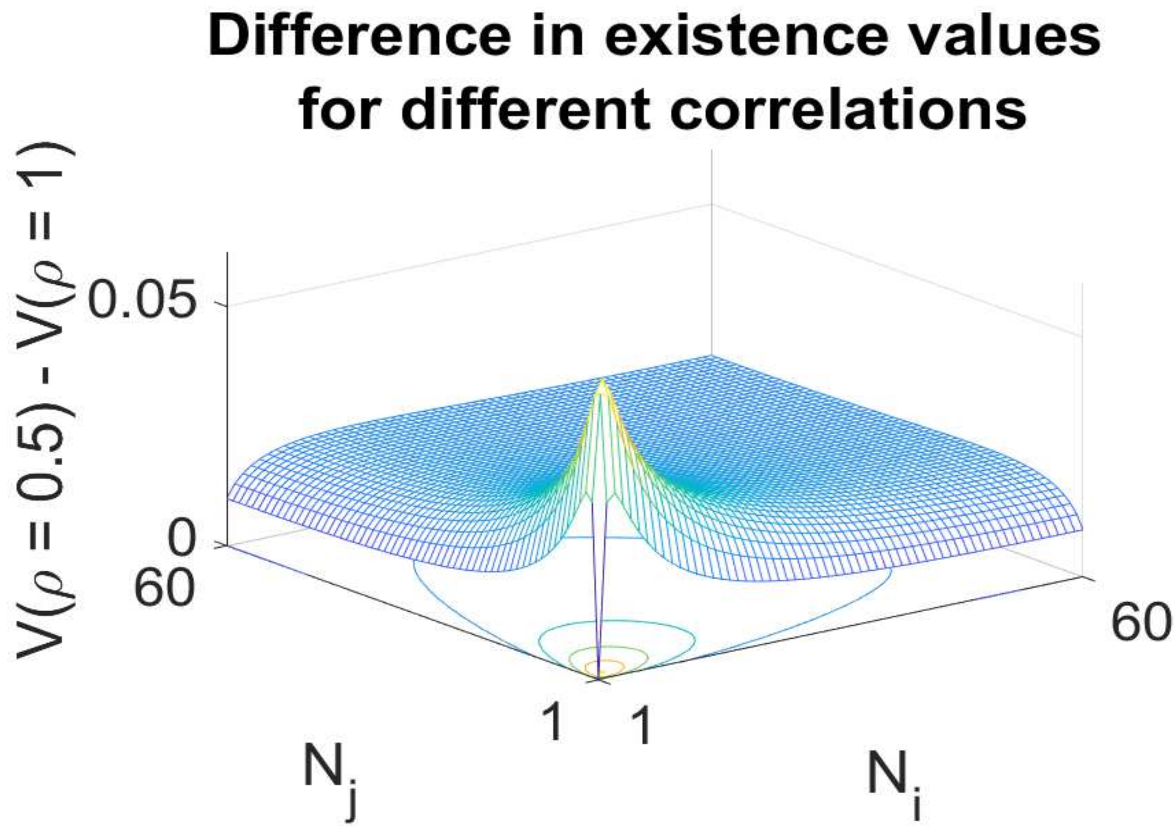

Multiple patch model - preliminary results summary

- Additional patches of habitat increase overall species value
  - due to additional local ”existence value”
  - . . . and also to reduction in extinction risk, particularly for low N_i, N_j
- As for single patch, overall species value is:
  - higher for lower risk
  - higher γ (more concave value function) increases value and increases impact of differences in risk
- Multiple patch value higher for lower correlation ρ
  - Diversification effect

Conclusions

Higher risk (due to climatic variation) likely to **decrease** the "value" of many natural processes related to land/habitat

- Value functions concave, due to natural upper bound on level of ESS flow
- . . . so increased risk increases downside costs with limited upside benefit

Implications:

- **Risk-reducing** measures **increase values** of natural processes
- Measures which **increase resilience** i.e. reduce the impact of risk are also value-enhancing
- **Greater risk** increases effectiveness of measures which increase resilience, so makes **investing in resilience-enhancing measures more worthwhile**

Future work

Future work

- More realistic population evolution in multi-patch model
- Incoroporation of relocation between patches (assisted immigration) and the interaction between this and other habitat enhancement measures
- Incorporation of movement between patches to investigate value effects of patch connectivity