OPTIMAL RESTORATION OF NATURAL ASSETS

Habitat Restoration in Europe

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Based on a joint work with *Pauli Lappi* (Reversing the tragedy of the commons: On optimal restoration of natural assets)

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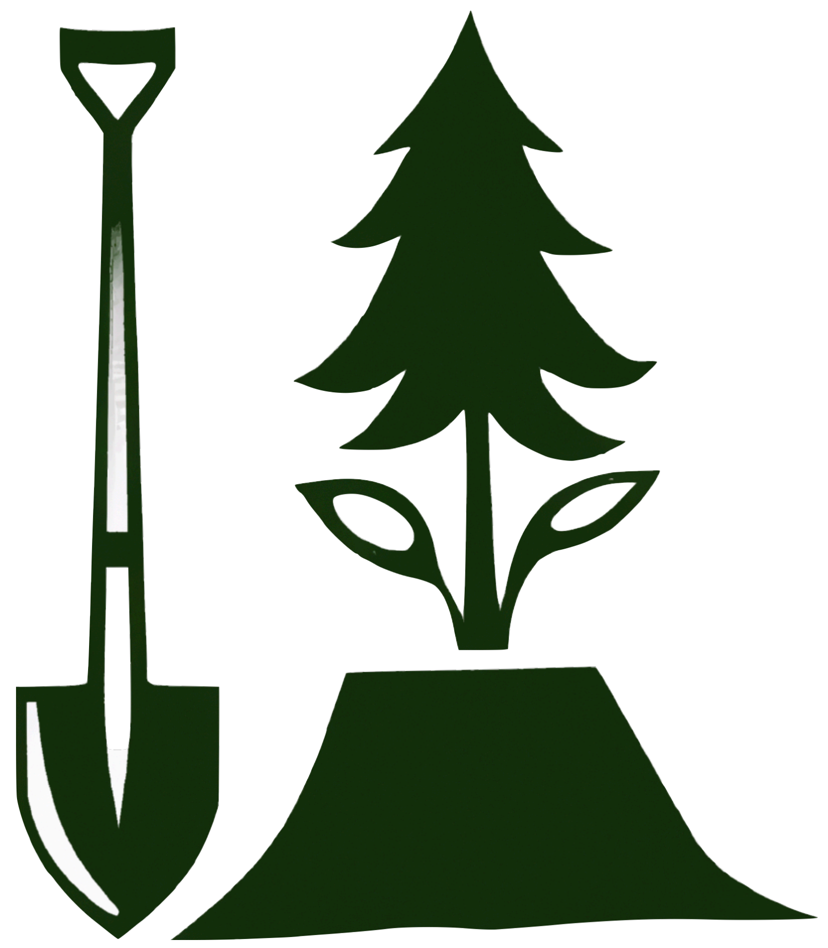
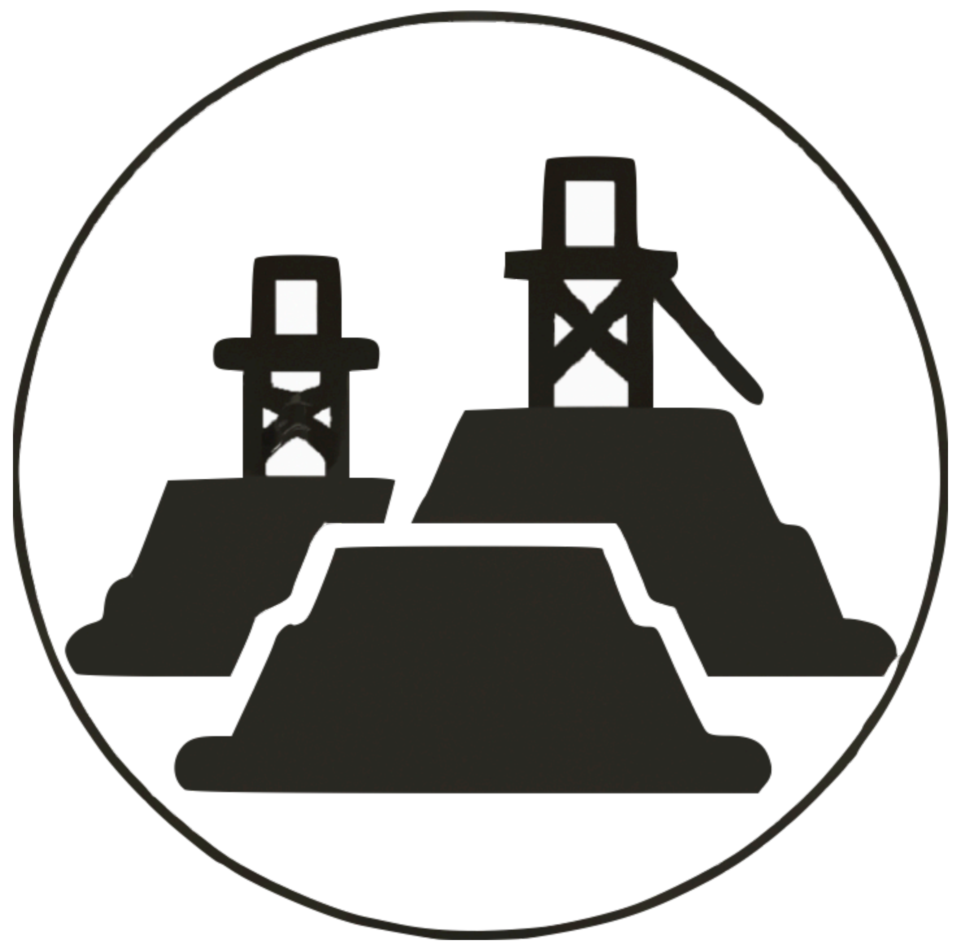
RESTORATION OF NATURAL ASSETS



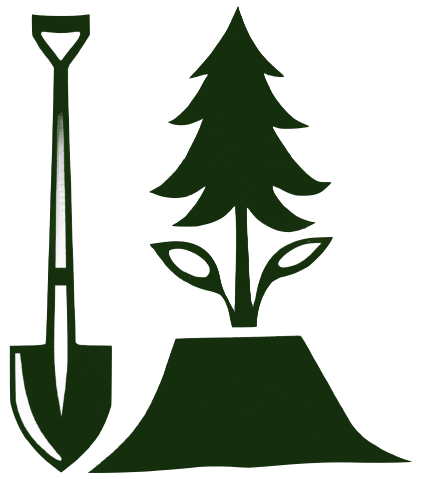
degenerated ecosystems and biodiversity



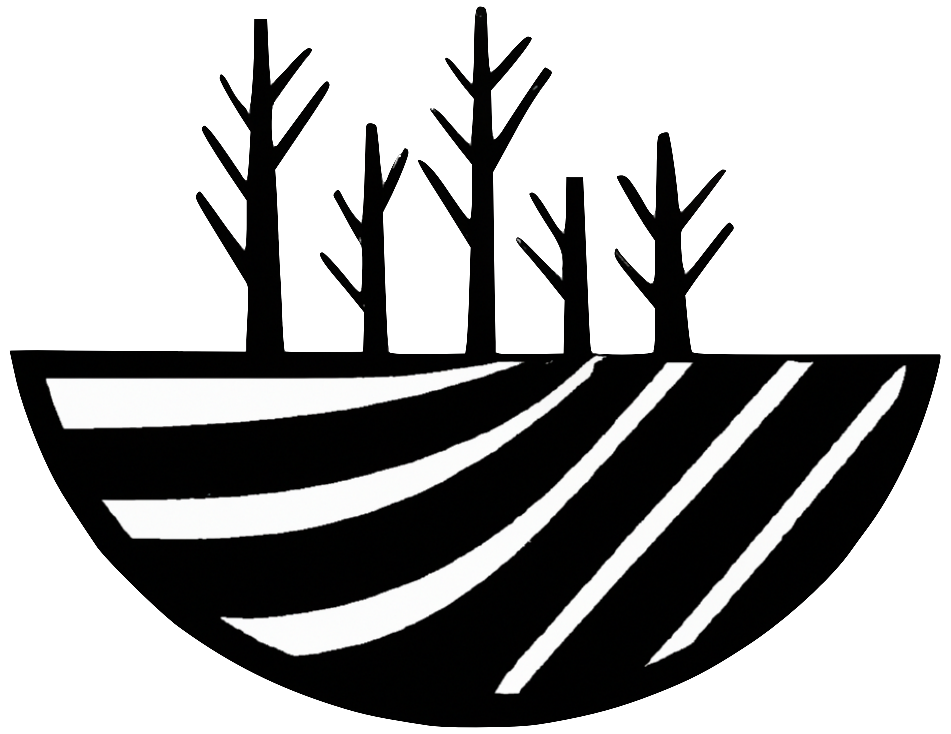
contaminated sites

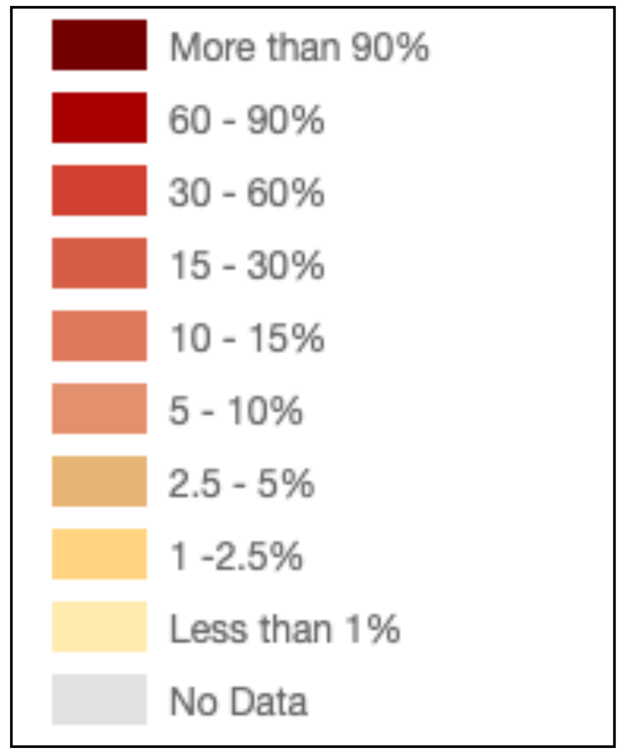
- No responsible party
- Restoration investments are costly
- One can rely also on natural regeneration or attenuation processes

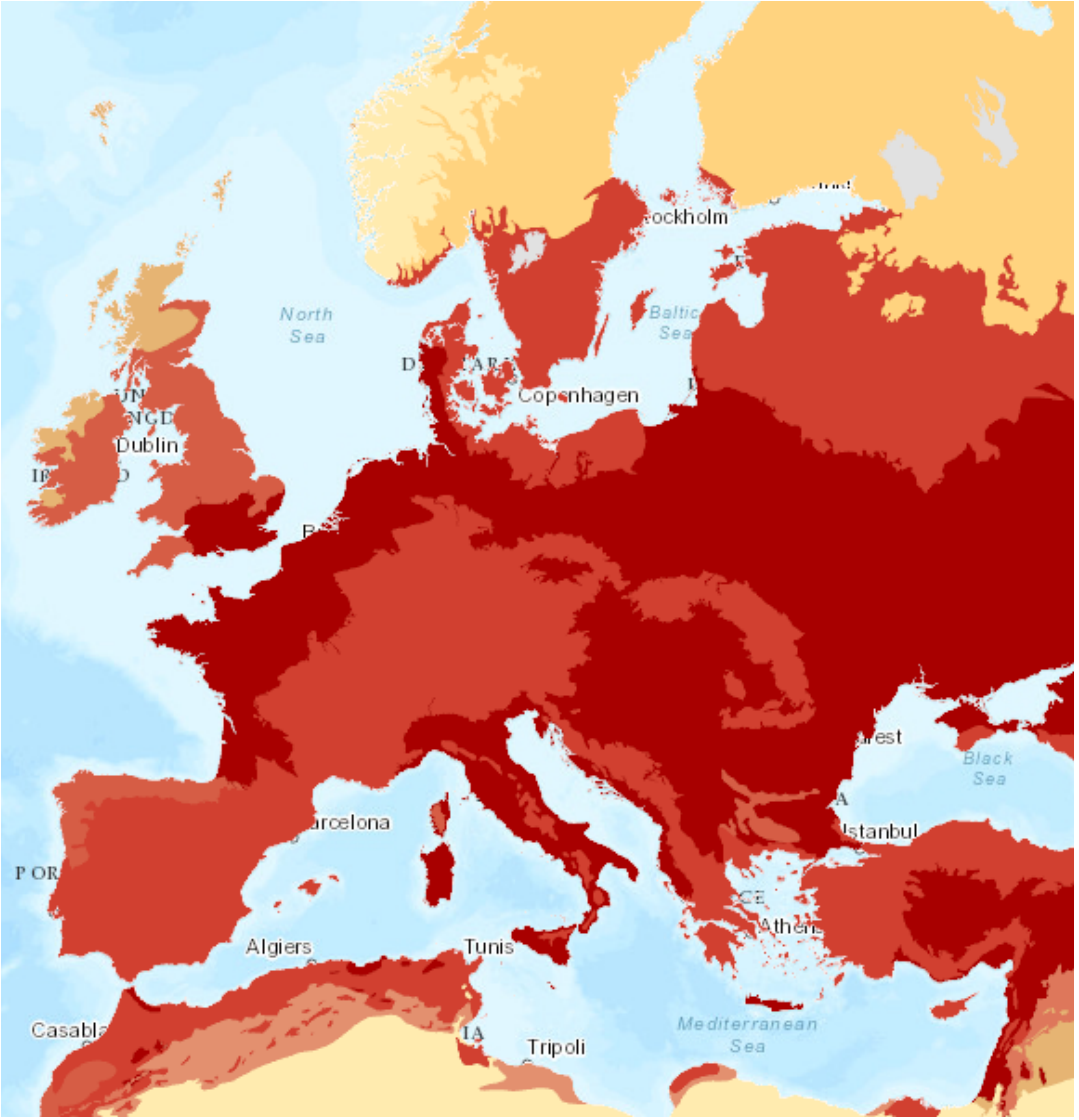
HABITAT RESTORATION IN EUROPE



Percent habitat loss by terrestrial ecoregion, The Nature Conservancy (2009)

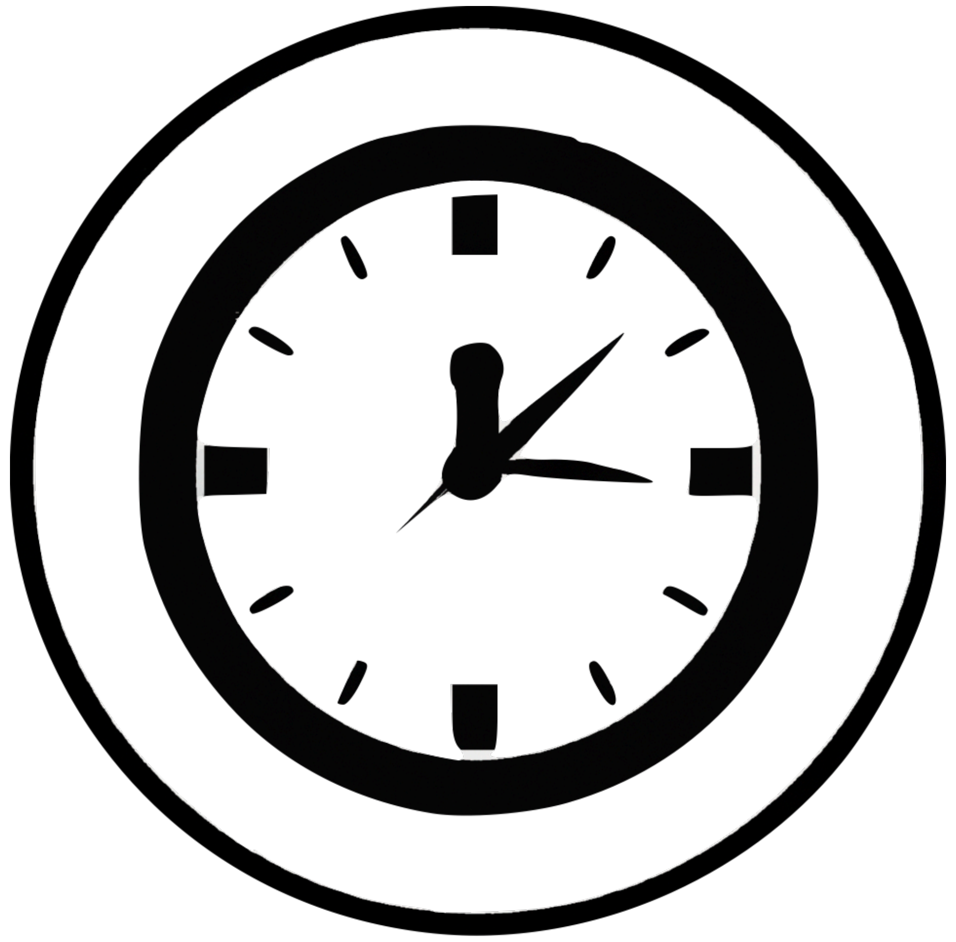




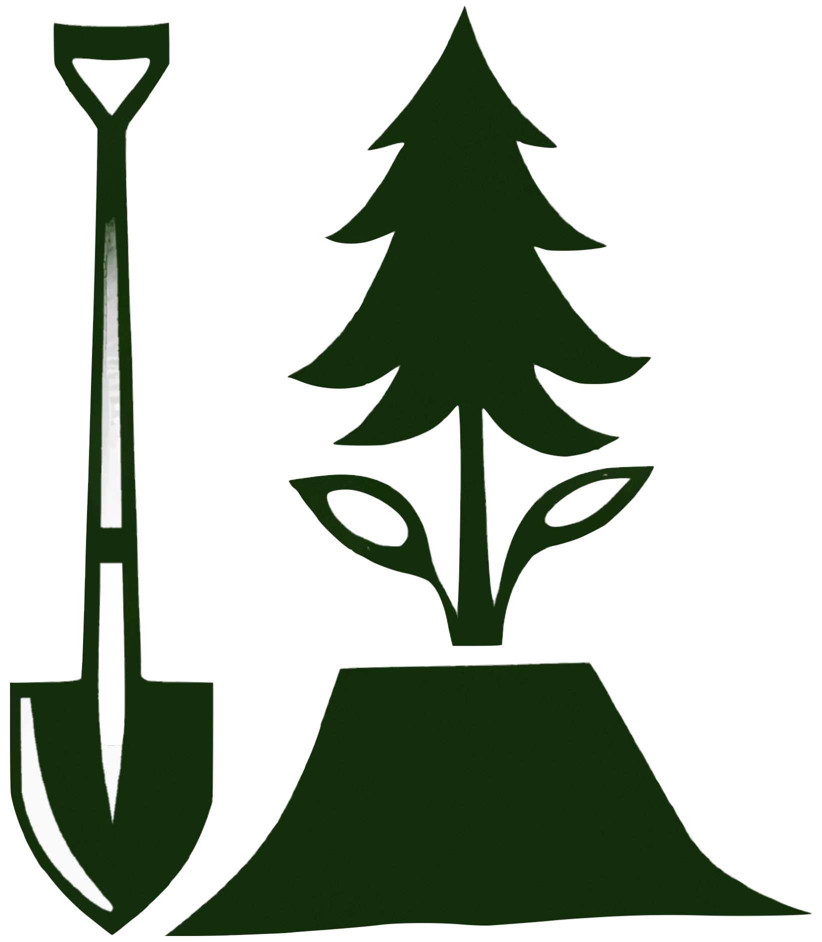


DECISION MAKER

has a fixed budget.



chooses the timing



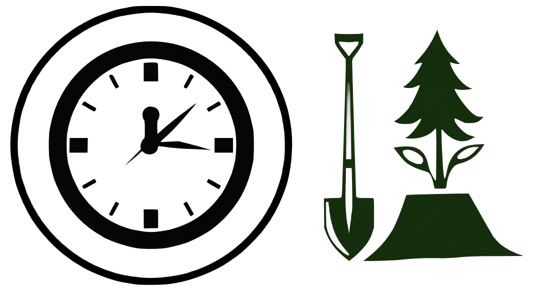
the level of restoration investment

and which sites are restored.

DECISION MAKER'S GOAL

- The decision maker wants to **minimise the loss function** under budget restriction.
- In our general model the loss function satisfies

$$\inf_{\{(\tau_i,k_i)_{i=1}^s\}} \mathscr{W}\left((\tau_i, k_i)_{i=1}^s\right)$$

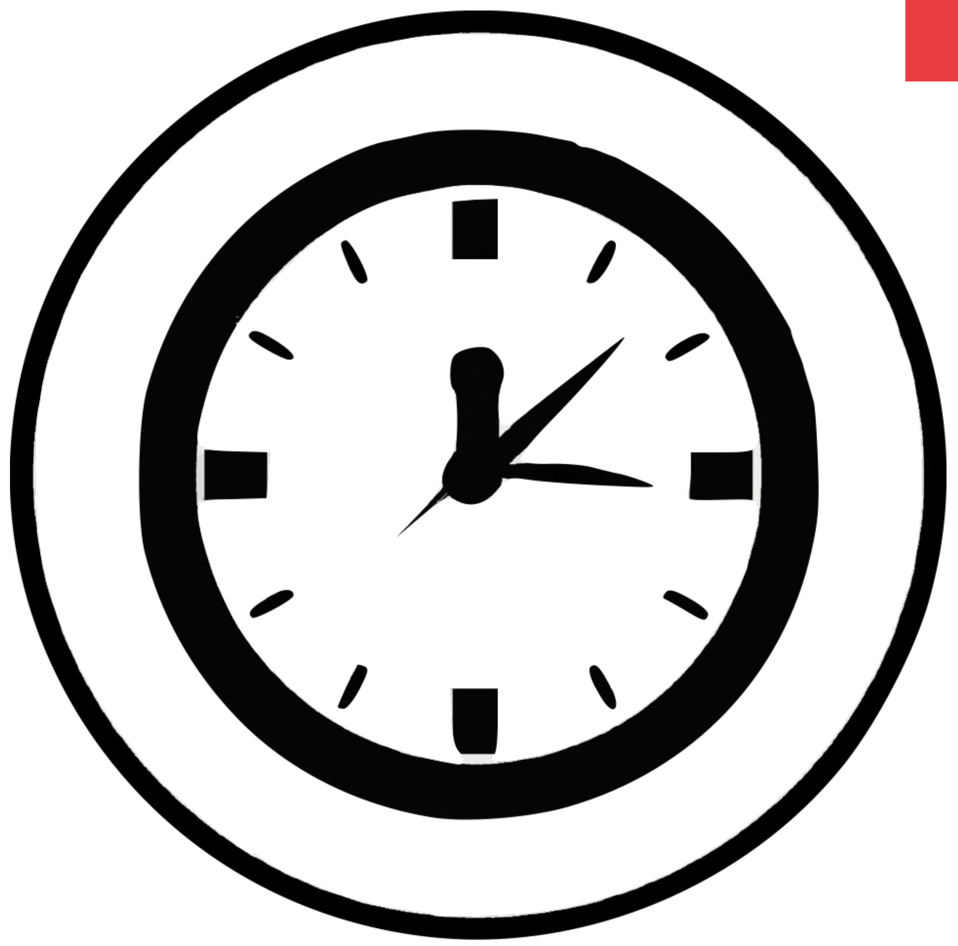
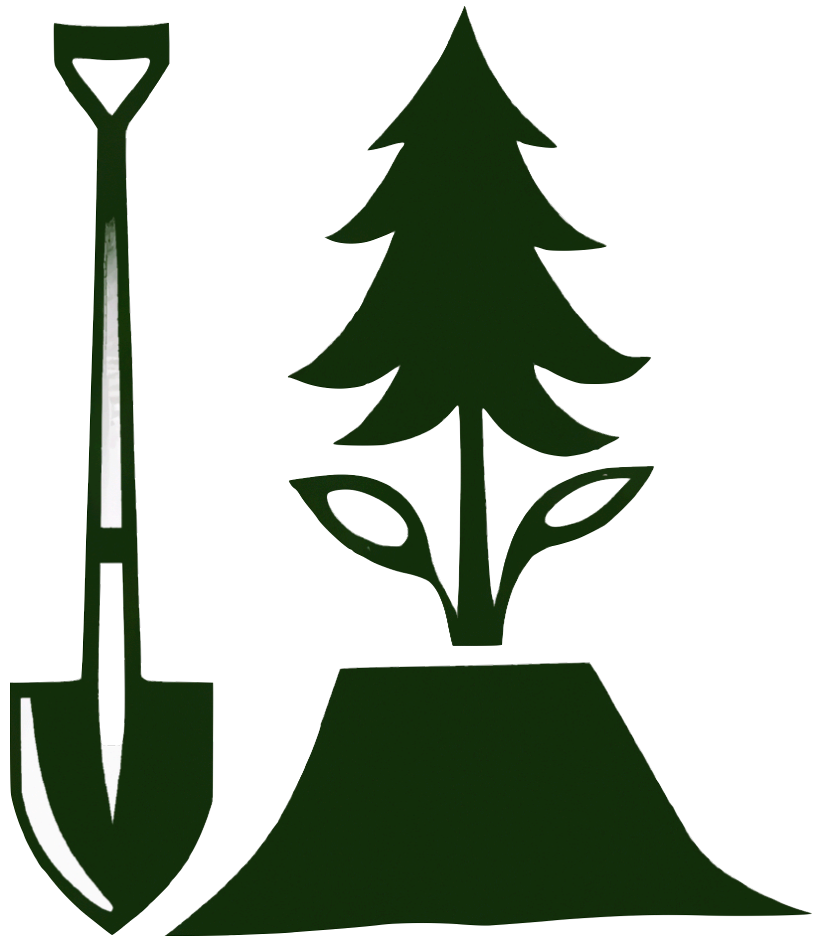


$$\partial_{\tau_i} \mathscr{W}((\tau_i, k_i)_{i=1}^s) > 0$$

$$\partial_{k_i} \mathscr{W}((\tau_i, k_i)_{i=1}^s) < 0$$

DECISION MAKER

EU

has a fixed budget. chooses the timing the level of restoration investment and which sites are restored.

10 billion euros

Goal: an optimal allocation of biodiversity restoration funds (i.e., the budget) between ecoregions in Europe

Norden 50 million euros

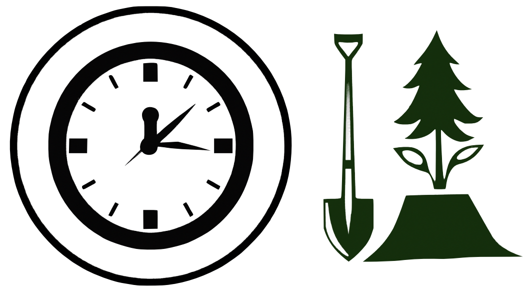
GOAL

- The decision maker wants to **minimise the expected number of lost value** of species.
- Each species have the same value (contrary to Weitzman's (1998) framework for the conservation under limited funds), we normalise this to the unity and discount

$$\int_0^{\dagger} e^{-rt}\, \mathrm{d}t$$

- The extinction of each species is uncertain and depends on the available habitat. The expected value of species is given by

$$\mathbb{E}\left(\int_0^{\dagger} e^{-rt}\, \mathrm{d}t\right) = \int_0^{\infty}\left(\int_0^{\dagger} e^{-rt}\, \mathrm{d}t\right) \mathrm{d}F(\dagger; \tau, k)\ \mathrm{d}\dagger$$



GOAL

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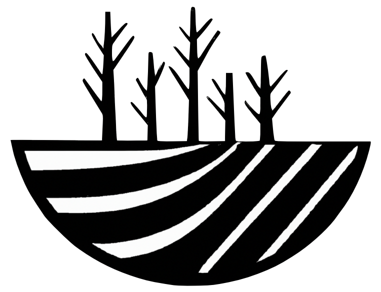
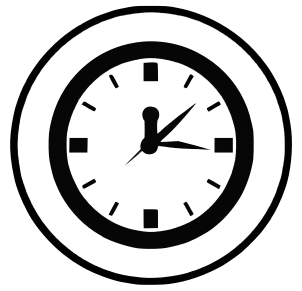


$$\mathbb{E}\left(\int_0^{\dagger} e^{-rt}\ \mathrm{d}t\right) = \int_0^{\infty}\left(\int_0^{\dagger} e^{-rt}\ \mathrm{d}t\right)\mathrm{d}F(\dagger;\tau,k)\ \mathrm{d}\dagger$$

- The cumulative probability distribution of death dates

$$F(\dagger;\tau,k) = \begin{cases} 1 - e^{-\rho n_0 \dagger}, & \dagger \le \tau \\ 1 - e^{-\rho n_0 \tau - \int_{\tau}^{\dagger} \rho N(s;\tau,k)\ \mathrm{d}s}, & \dagger > \tau \end{cases}$$



- The power of the exponential comes from the intensity, e.g,

$$P(\dagger \in (s, s+\mathrm{d}s) \mid \dagger > s) = \rho\ N(s;\tau,k)\ \mathrm{d}s + \mathrm{d}s\ E(\mathrm{d}s)$$

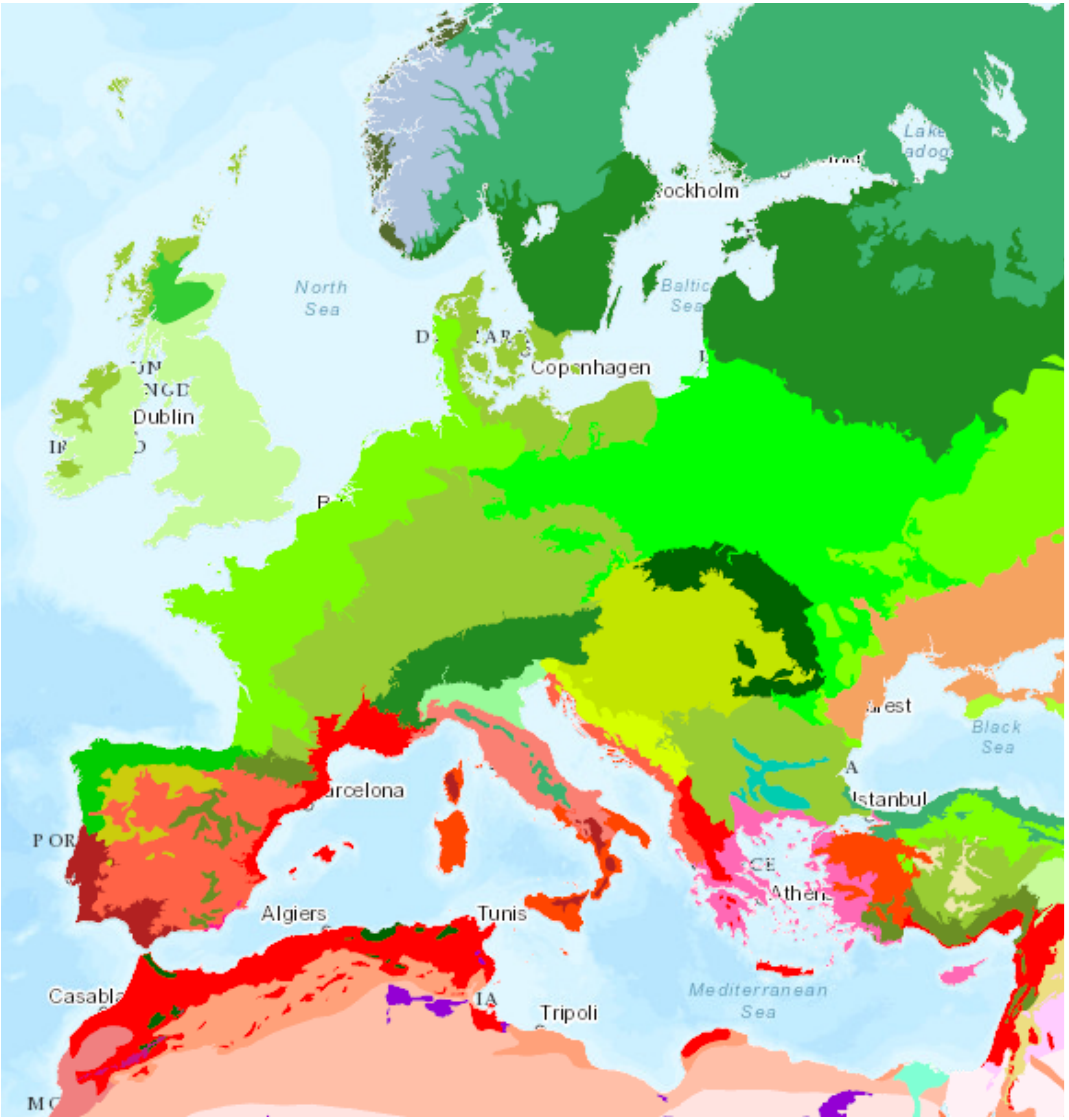
46 TERRESTRIAL ECOREGIONS IN EUROPE

EU, UK, EFTA and CEFTA countries

"relatively large units of land containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change"

–Olson et al. (2001)

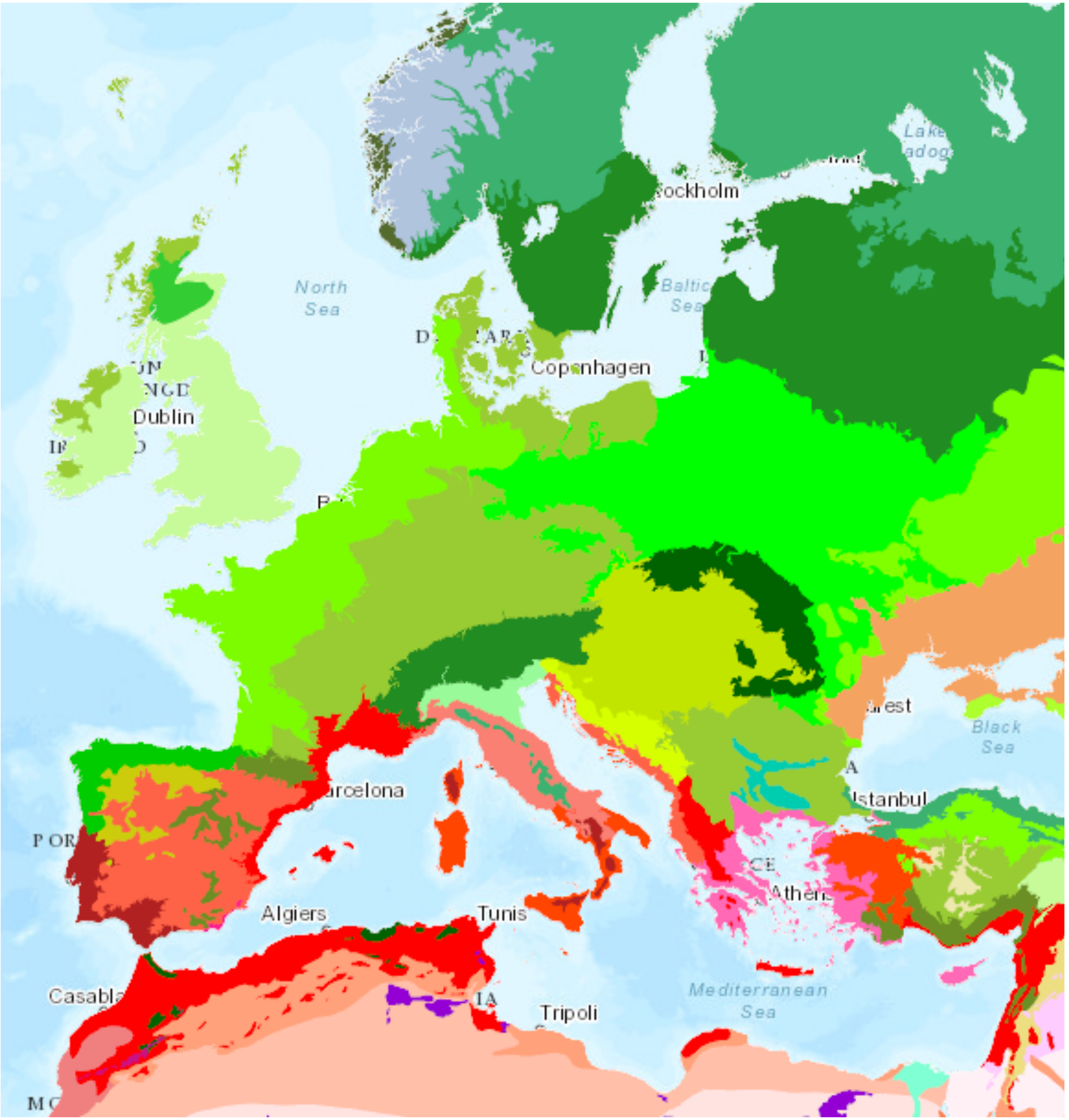
Conservation Science Program - World Wildlife Fund



SPECIES

Kier et al. (2005) plant data on vascular plant species for each ecoregion: approximately 80 000 species altogether and values range from 330 (e.g., Faroe Island Boreal Grassland) to 5 000 (e.g., Alps Conifer and Mixed Forest) per ecoregion.

Conservation Science Program - World Wildlife Fund



BUDGET RESTRICTION

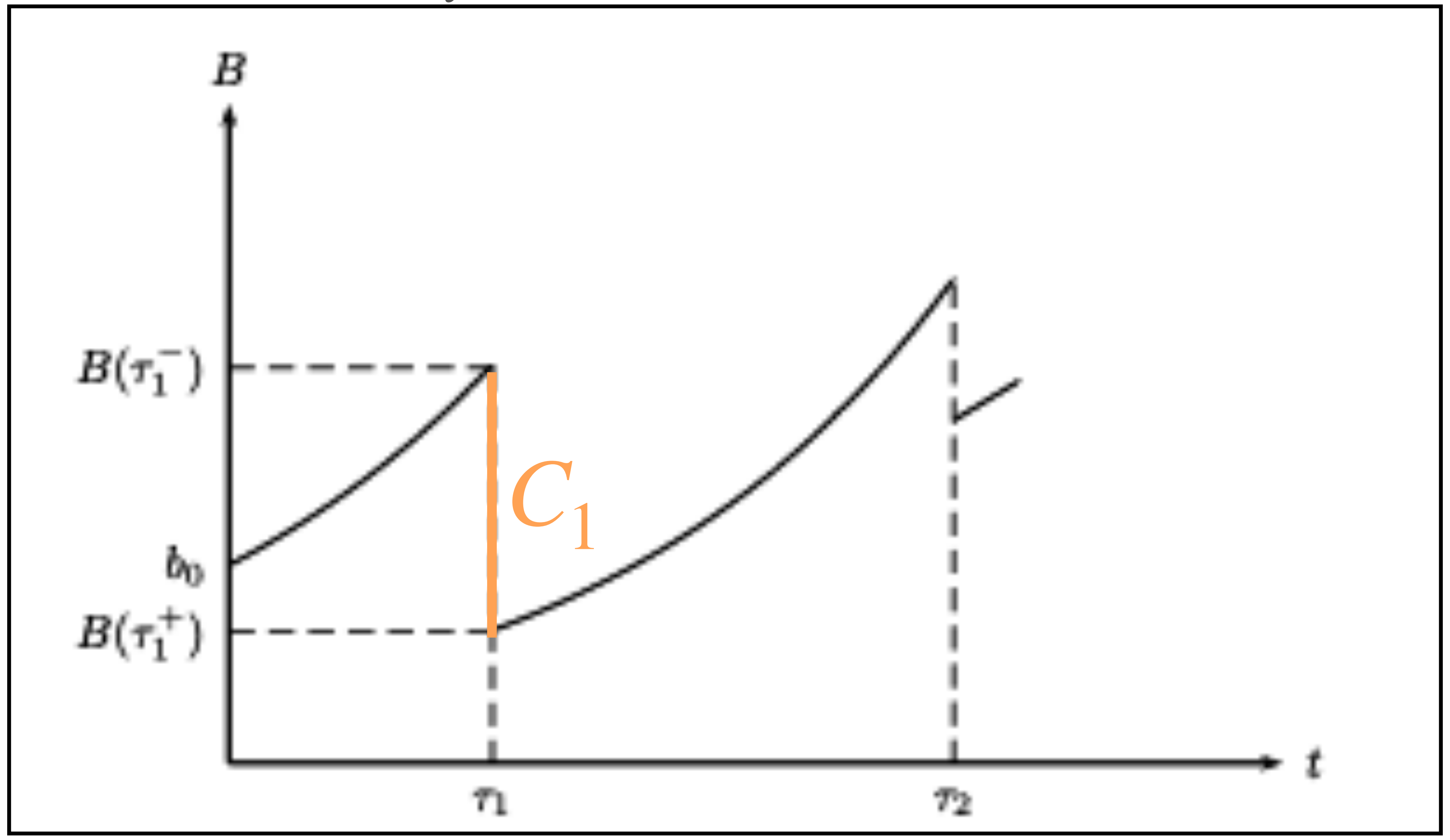
In our general model the cost function is increasing and ultimately convex in k_i.

- **The restoration cost** is increasing and convex in the area brought under restoration and decreasing in the lost habitat area that is not restored, similar as in Harstad (2023)

$$C_i(k_i, n_i) = \frac{c_i(k_i\, n_{i,0}\, A_i)^2}{(1-k_i)n_{i,0}A_i} = c_i\, n_{i,0}\, A_i \frac{k_i^2}{1-k_i}$$

average cost of agricultural land (Eurostat)

- Available budget drops by the restoration cost at the restoration date, but raises by the rate of interest in between dates



LOSS FUNCTION IN NUMERICS

- The decision maker wants to **minimise the expected number of lost species** at the end of the planning interval (e.g.,10 years) — vs. the discounted lost value
- The loss function is the expected number of lost species, e.g., Costello & Polasky (2004), Luby & al. (2022)
- Probability to survive = { the current habitat size / the original habitat size } to the power 0.2, by the ecological research, e.g., Strassburg et al. (2020) and Luby et al. (2022).
- The current habitat = original – lost + area under restoration – dynamics of restoration

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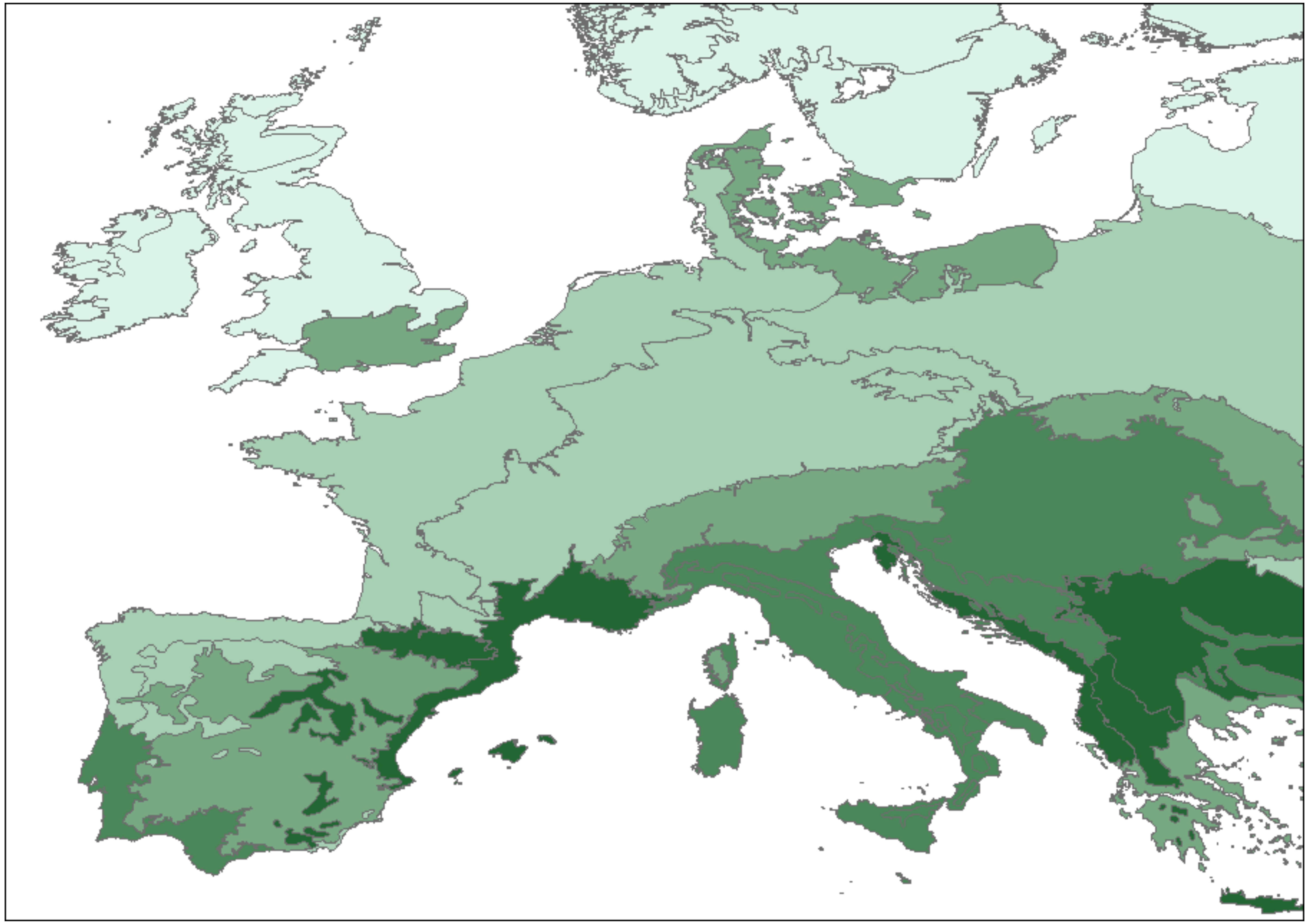
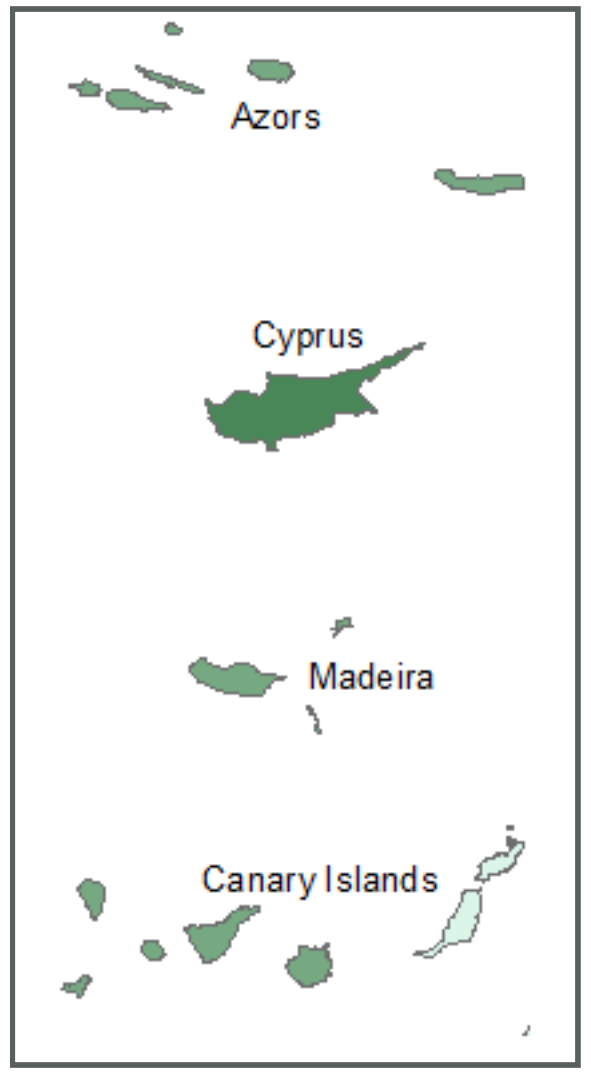
$\mathscr{W}((\tau_i, k_i)_{i=1}^{46}) =$ sum of all species [a species does not survive in any region]

$$= \sum_{i=1}^{46} (\#\text{ endemic species in the region } i) \left[1 - \left\{ 1 - \left((1-k_i)n_{i,0} + \frac{2k_i n_{i,0}}{1+e^{10-\tau_i}} \right) \right\}^{0.2} \right]$$



Approximately 8 750 lost species

Largest shares
- Illyrian Deciduous Forests (12%)
- Pindus Mountains Forests (8%)
- Crete Mediterranean Forests (7%)



Azores

Cyprus

Madeira

Canary Islands

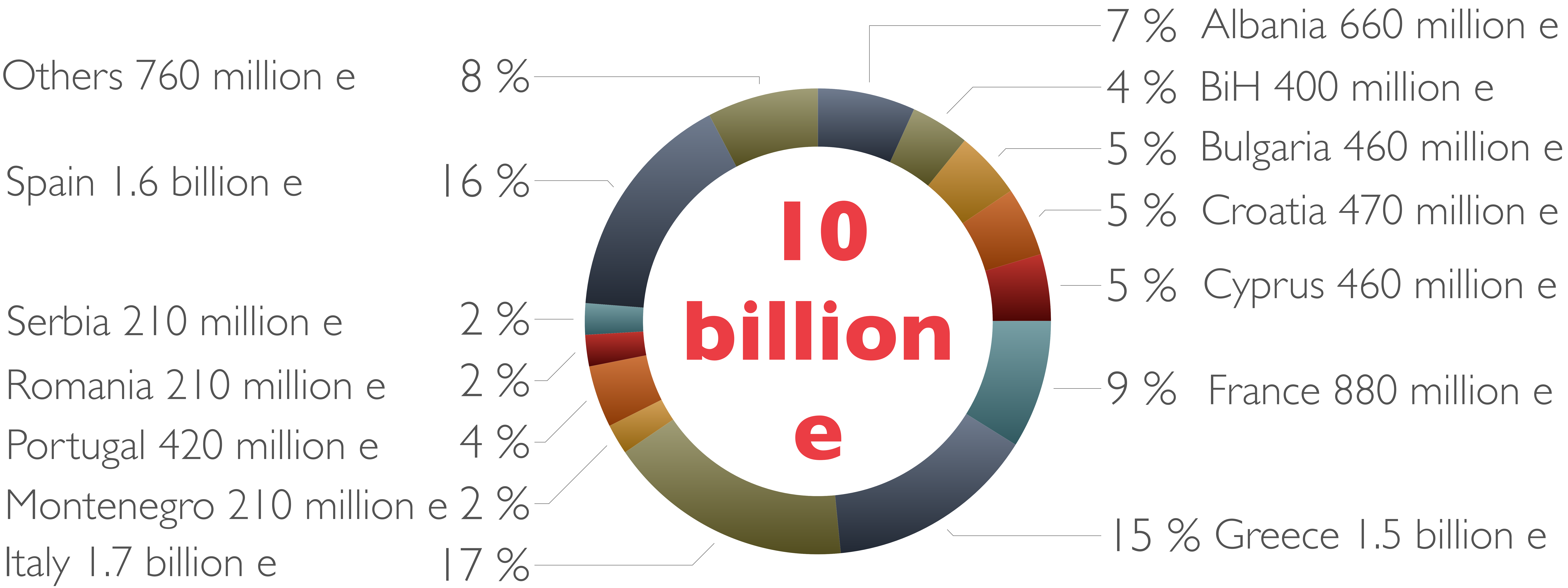
0%–0.2%
0.2%–0.8%
0.8%–2%
2%–5%
5%–12.2%

OPTIMAL ALLOCATION OF **10 BILLION E**

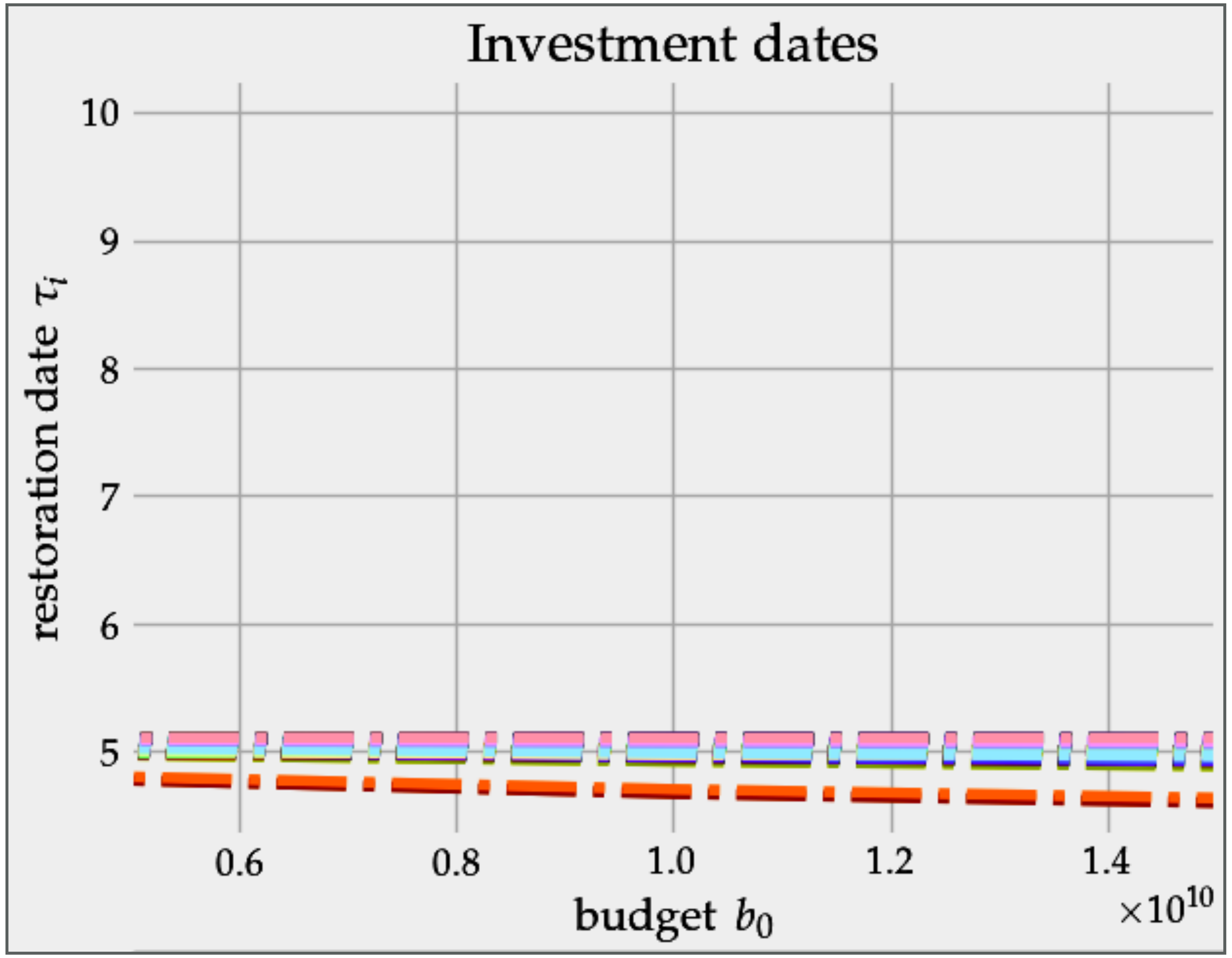
- Allocation is driven by
  1. The number of species 2. The cost 3. The lost habitat before restoration
- large 1, small 2, and large 3 $\Longrightarrow$ money

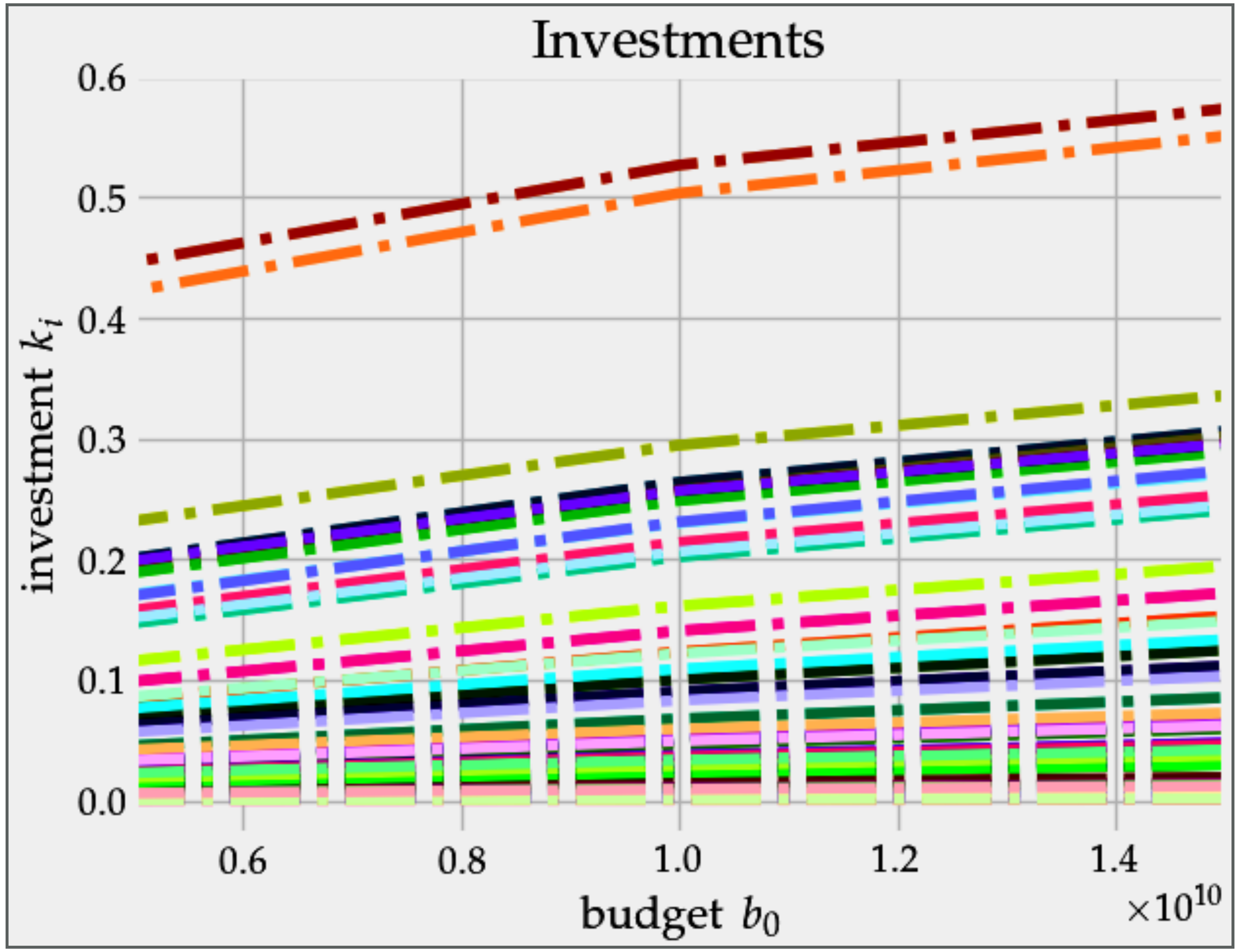
BUDGET SHARE FOR COUNTRIES

Nordic countries 50 million euros



TIMES AND EFFORTS





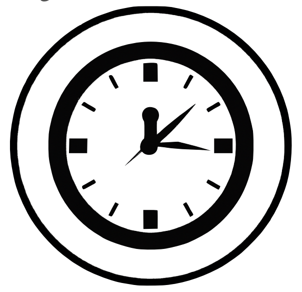
DECISION MAKER'S PROBLEM

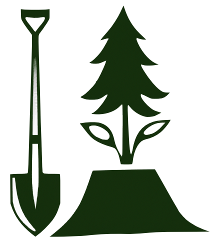
$$\inf_{\{(\tau_i,k_i)_{i=1}^s\}} \mathscr{W}\left((\tau_i, k_i)_{i=1}^s\right)$$

$$\dot{B} = rB \geq 0, \quad B(0^-) = b_0 > 0$$

$$B(\tau_i^-) - B(\tau_i^+) = C_i(k_i, N_i(\tau_i))$$

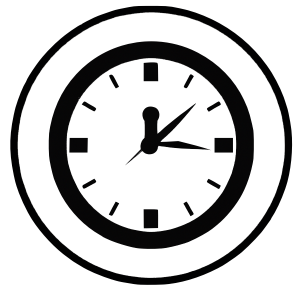
$$\tau_i \geq 0, \quad k_i \geq 0, \quad \text{for all } i.$$

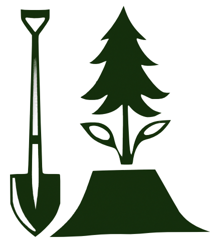




$$b_0 = \sum_{i=1}^{s} C_i(k_i, N_i(\tau_i))e^{-r\tau_i}$$

$$\tau_i \geq 0, \quad k_i \geq 0, \quad \text{for all } i.$$





Results

- Optimal waiting and investment rules
- A sufficient condition for restoration of a damaged stock
- A budget allocation formulation of the problem
- A test: "Is the budget allocation optimal?"

DATA

European Commissions's Digital Observatory for Protected Areas (DOPA)

- The Nature Conservancy (2009) habitat loss as a percent of the total ecoregion area
- Kier et al. (2005) plant data on vascular plant species for each ecoregion
- Eurostat's data on arable land prices

NUMERICS

- Python SciPy's Sequential Least Squares Programming (SLSQP) with tolerance 1e-7
- Artelys Knitro

MENTIONED REFERENCES

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