Reversing the tragedy of the commons

ON OPTIMAL RESTORATION OF NATURAL ASSETS

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joint work with *Pauli Lappi*

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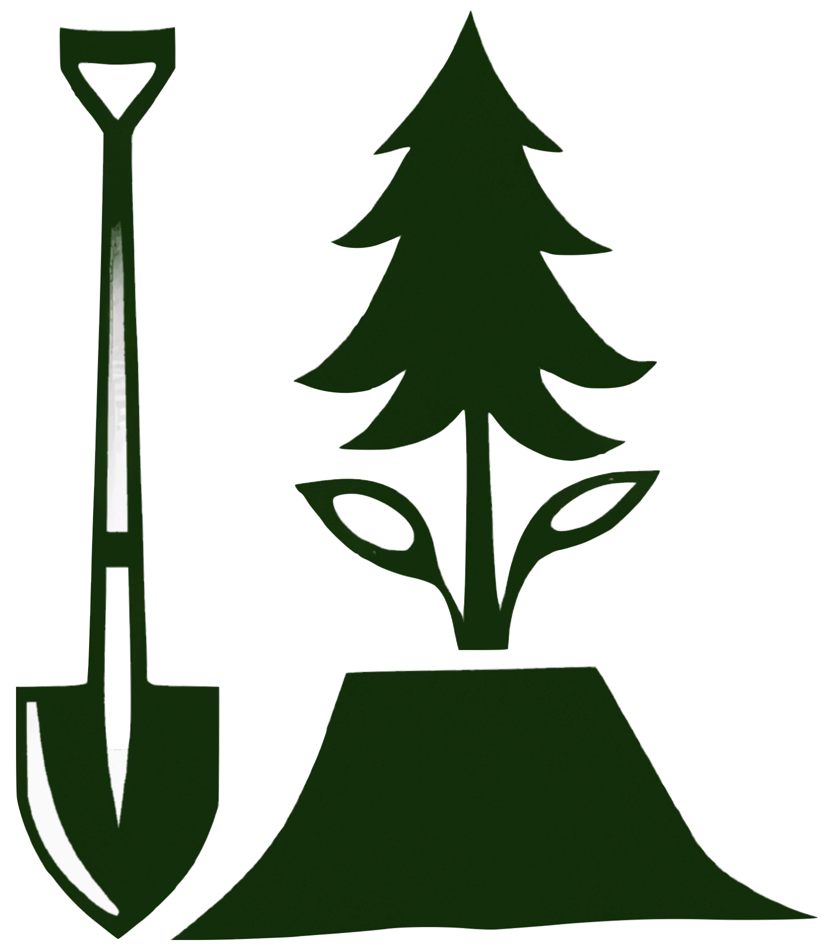
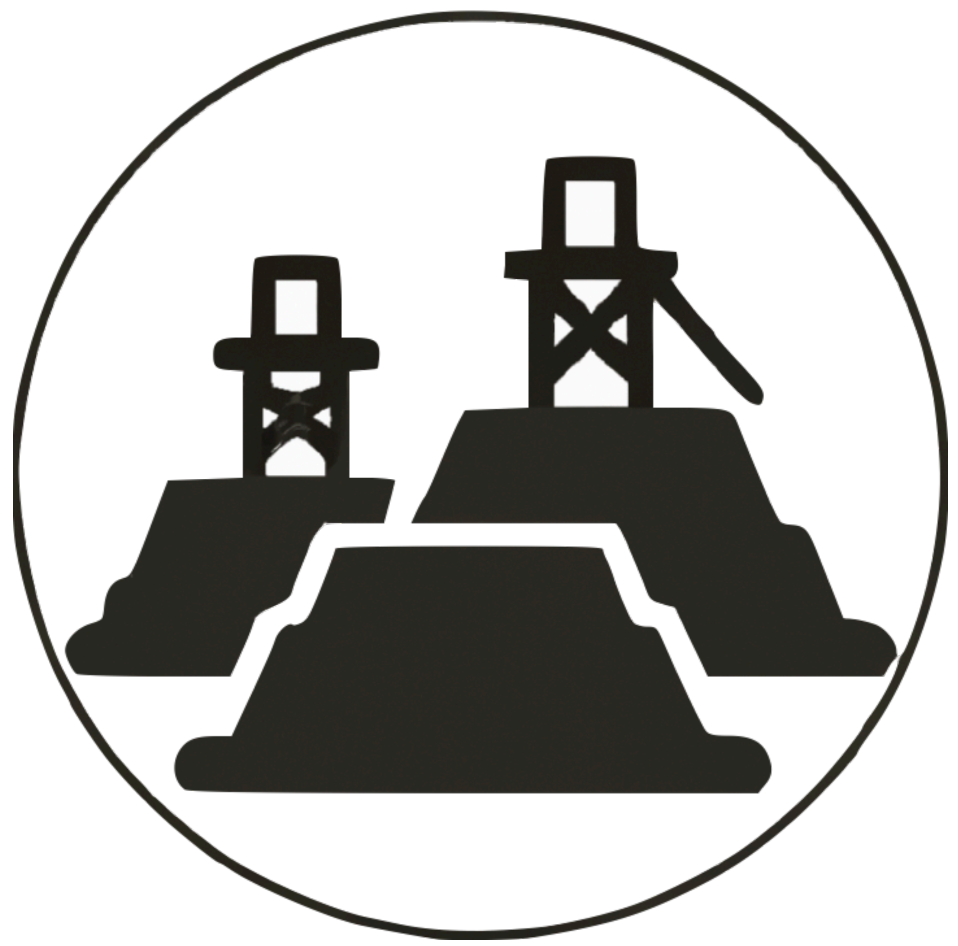
RESTORATION OF NATURAL ASSETS



degenerated ecosystems and biodiversity

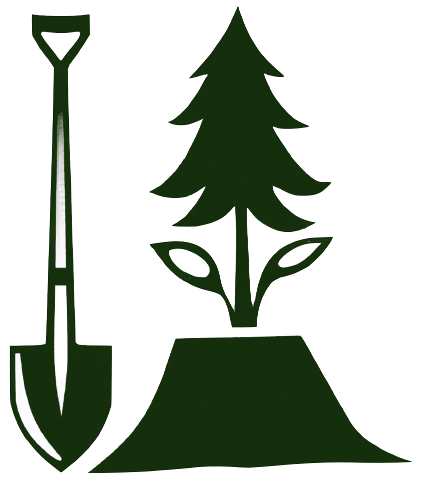


contaminated sites

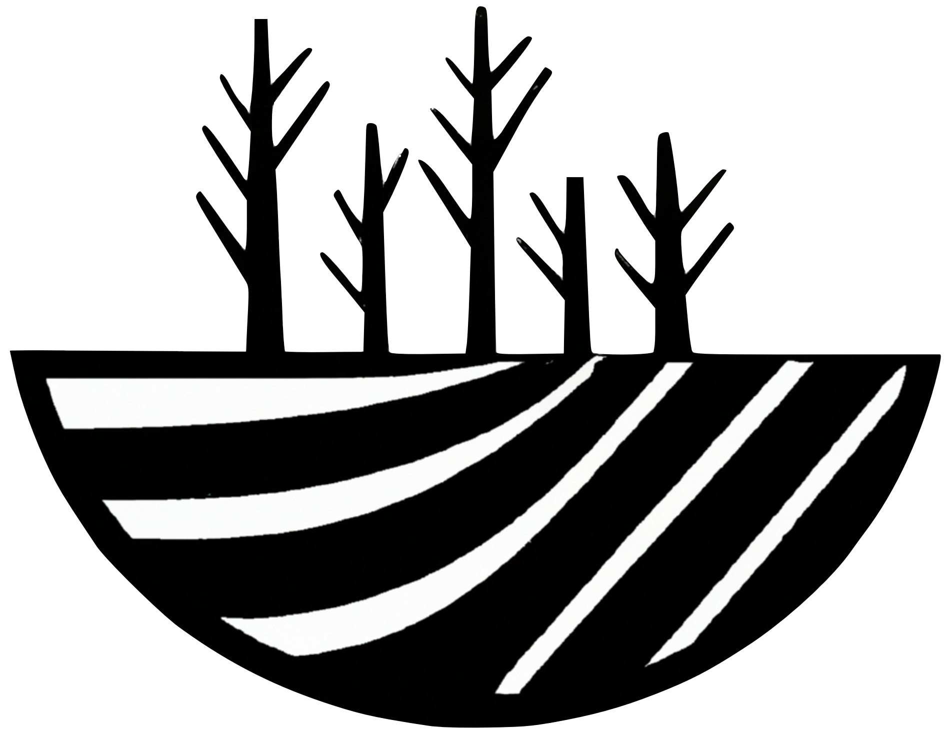
- No responsible party
- Restoration investments are costly
- One can rely also on natural regeneration or attenuation processes

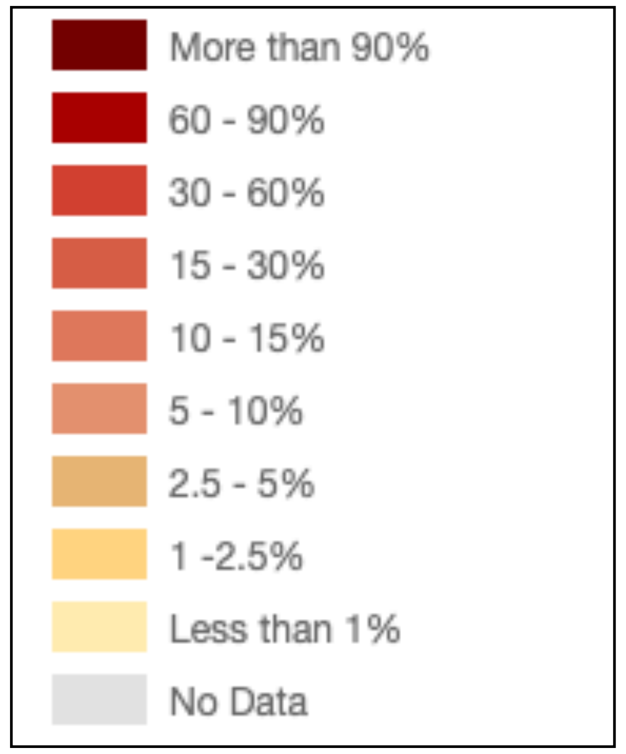
The Nature Conservancy

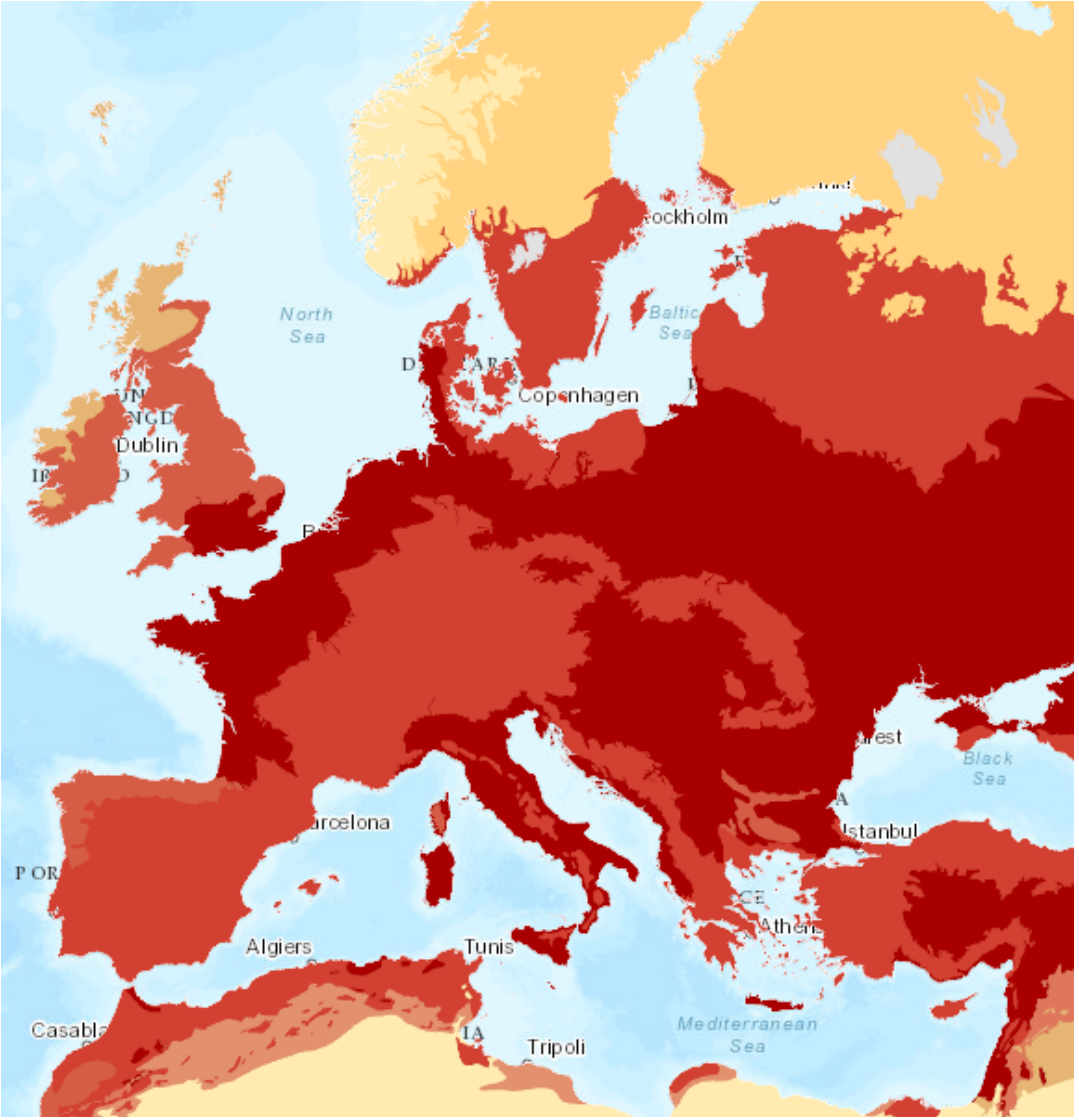
HABITAT RESTORATION IN EUROPE



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



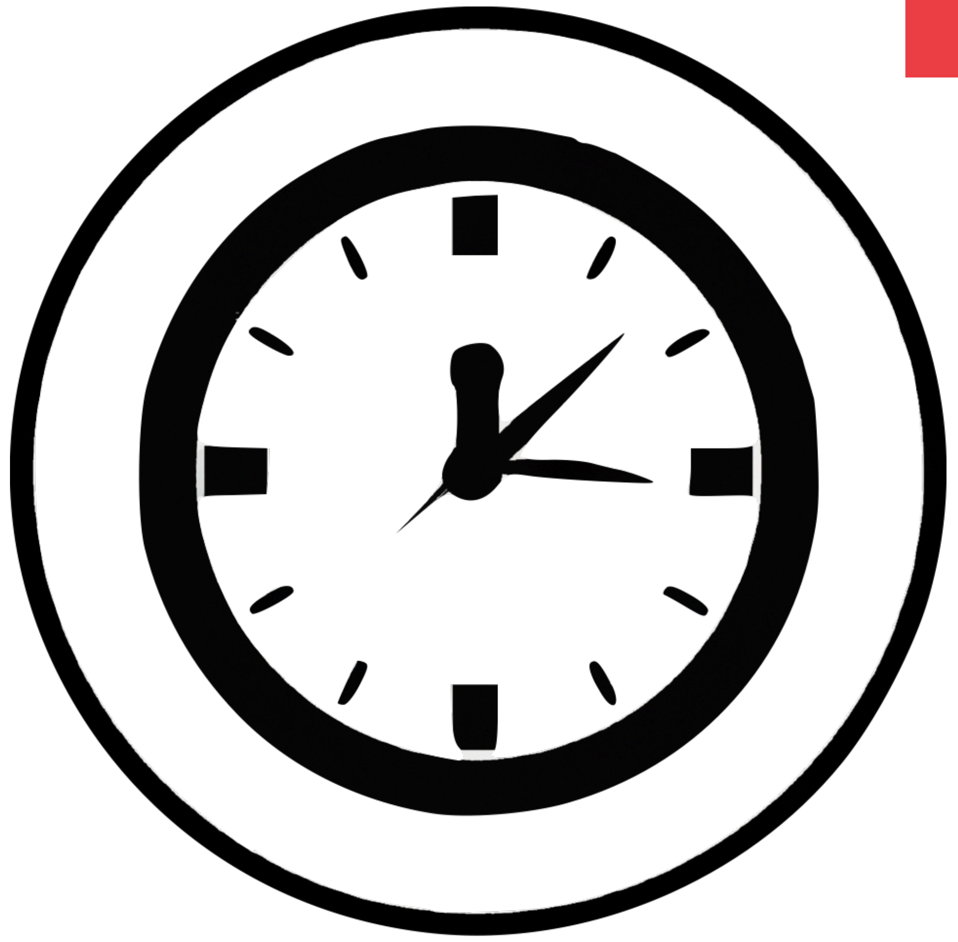




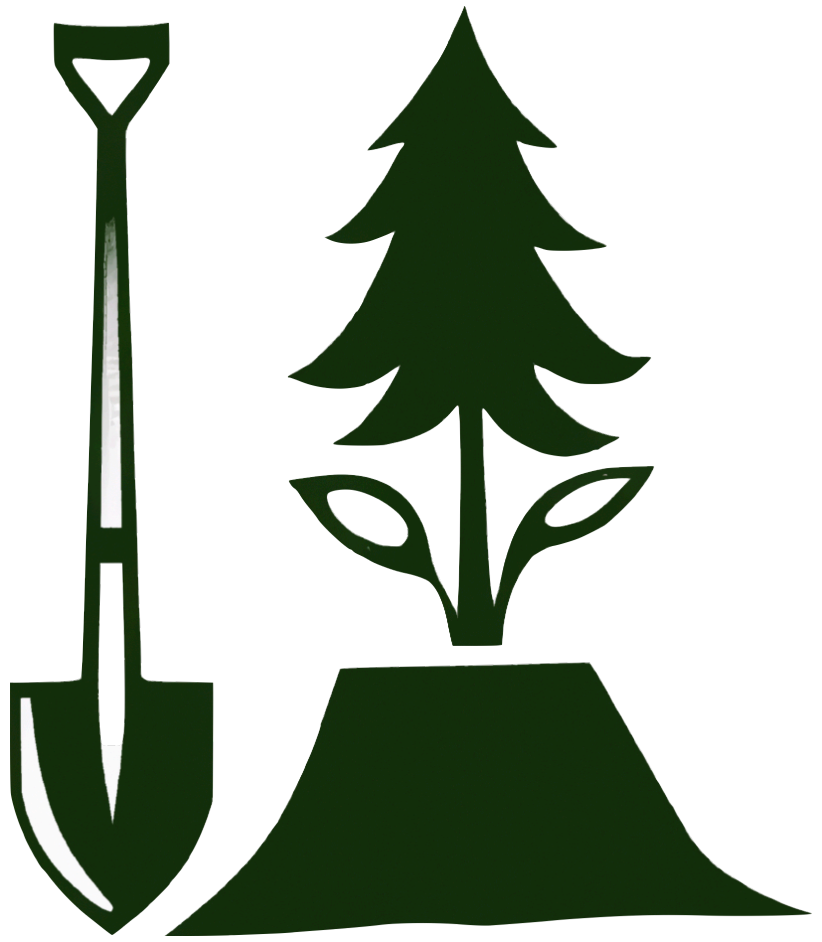
DECISION MAKER

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

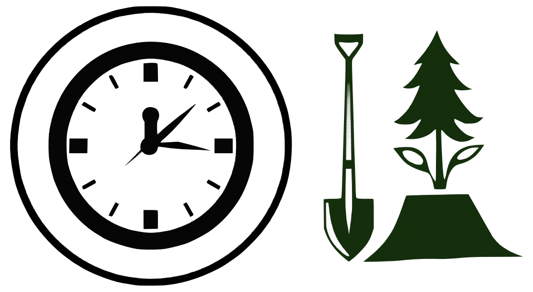
In our general model the loss function satisfies

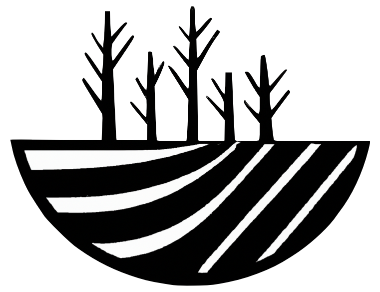
GOAL

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

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

- The decision maker wants to **minimise the expected number of lost species** at the end of the planning interval (the date T, for our example T = 10 years)
- The loss function is the expected number of lost species, e.g., Costello & Polasky (2004), Luby & al. (2022)





$$\mathscr{W}((\tau_i, k_i)_{i=1}^{s}) = \sum_{j \in \mathcal{S}} \left[\prod_{i=1}^{s} \left(1 - P_{ij}(N_i(T; \tau_i, k_i))\right) \right]$$

sum of all species [a species does not survive in any region]

- Each species have the same value (contrary to Weitzman's (1998) framework for the conservation under limited funds)

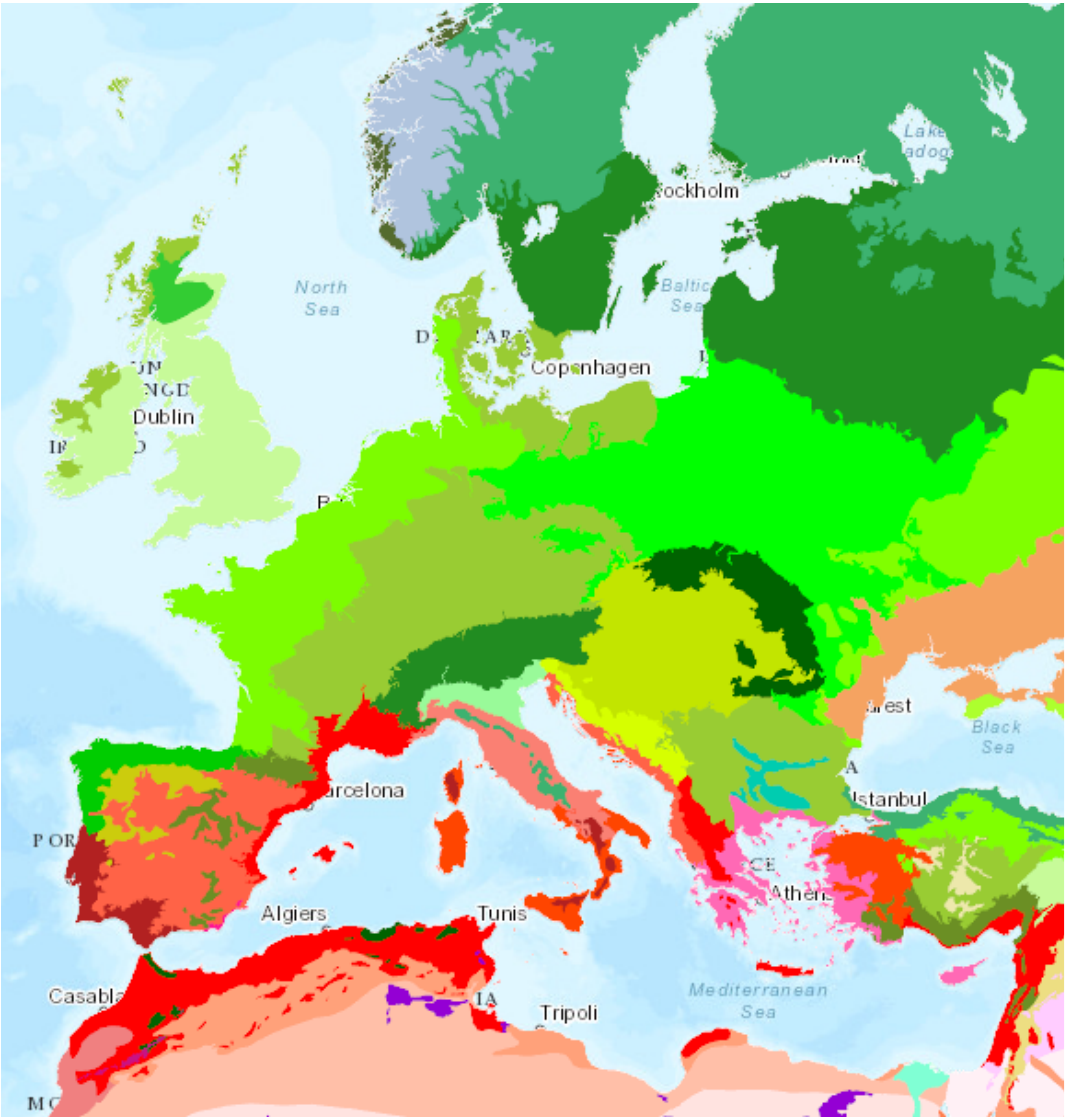
46 TERRESTRIAL ECOREGIONS IN EUROPE

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)

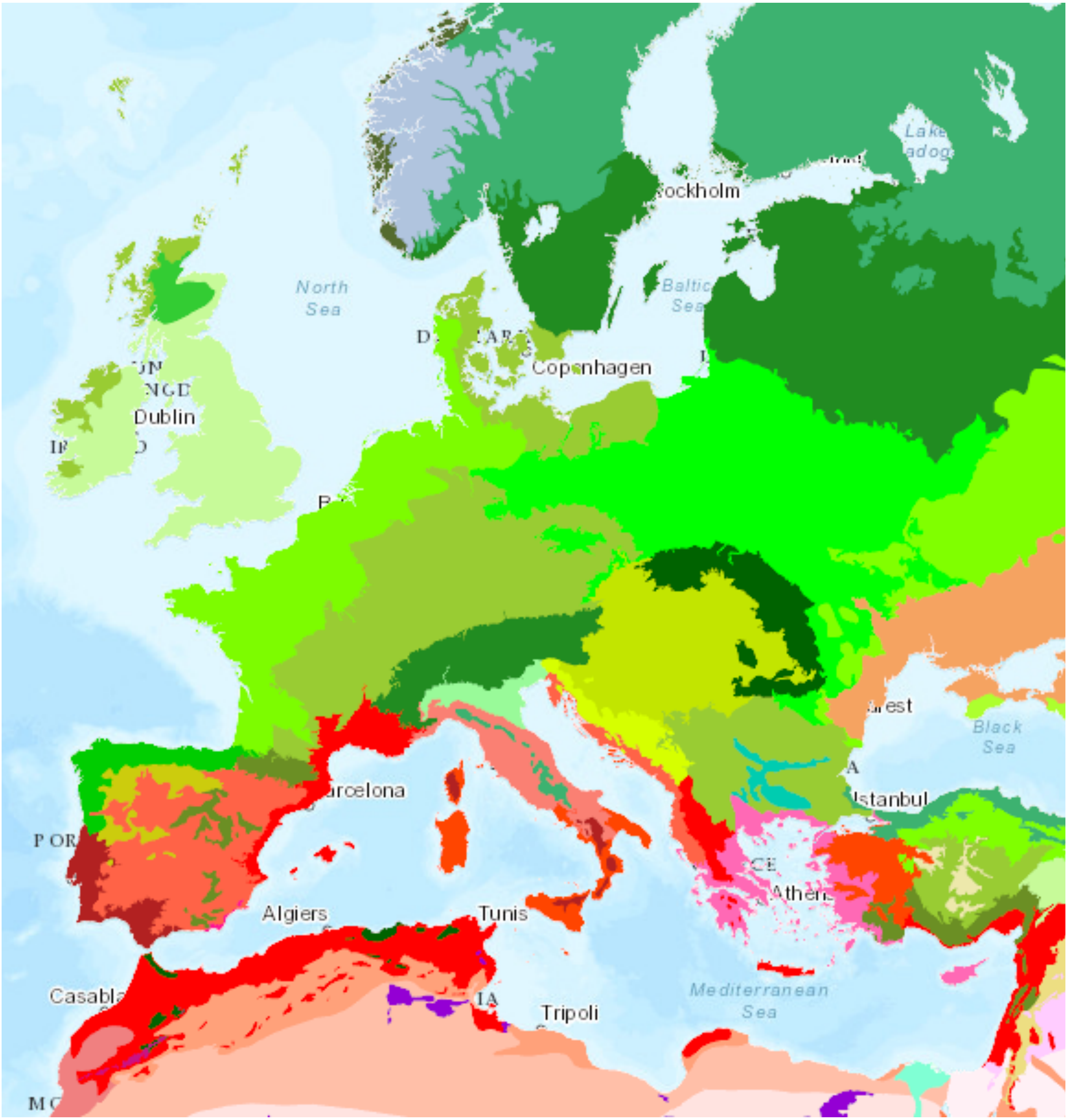
Conservation Science Program - World Wildlife Fund



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.

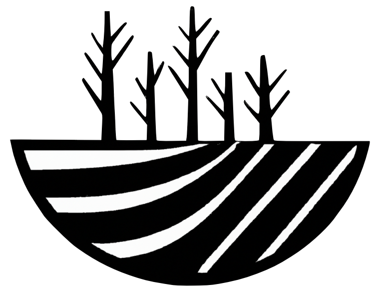
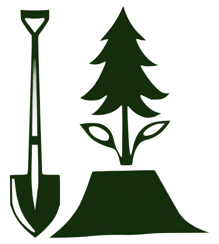
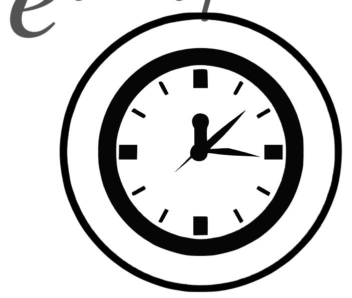
Conservation Science Program - World Wildlife Fund



EXPECTED NUMBER OF LOST SPECIES

- 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:

$$A_i - \left((1-k_i)n_{i,0}A_i + \frac{2k_i n_{i,0}}{1+e^{t-\tau_i}}A_i \right) = A_i - n_{i,0}A_i + k_i n_{i,0}A_i - \frac{2k_i n_{i,0}}{1+e^{t-\tau_i}}A_i$$

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

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

BUDGET RESTRICTION

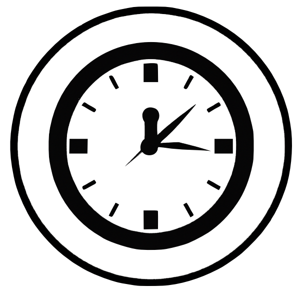
In our general model the cost function is increasing and ultimately convex in k_i.

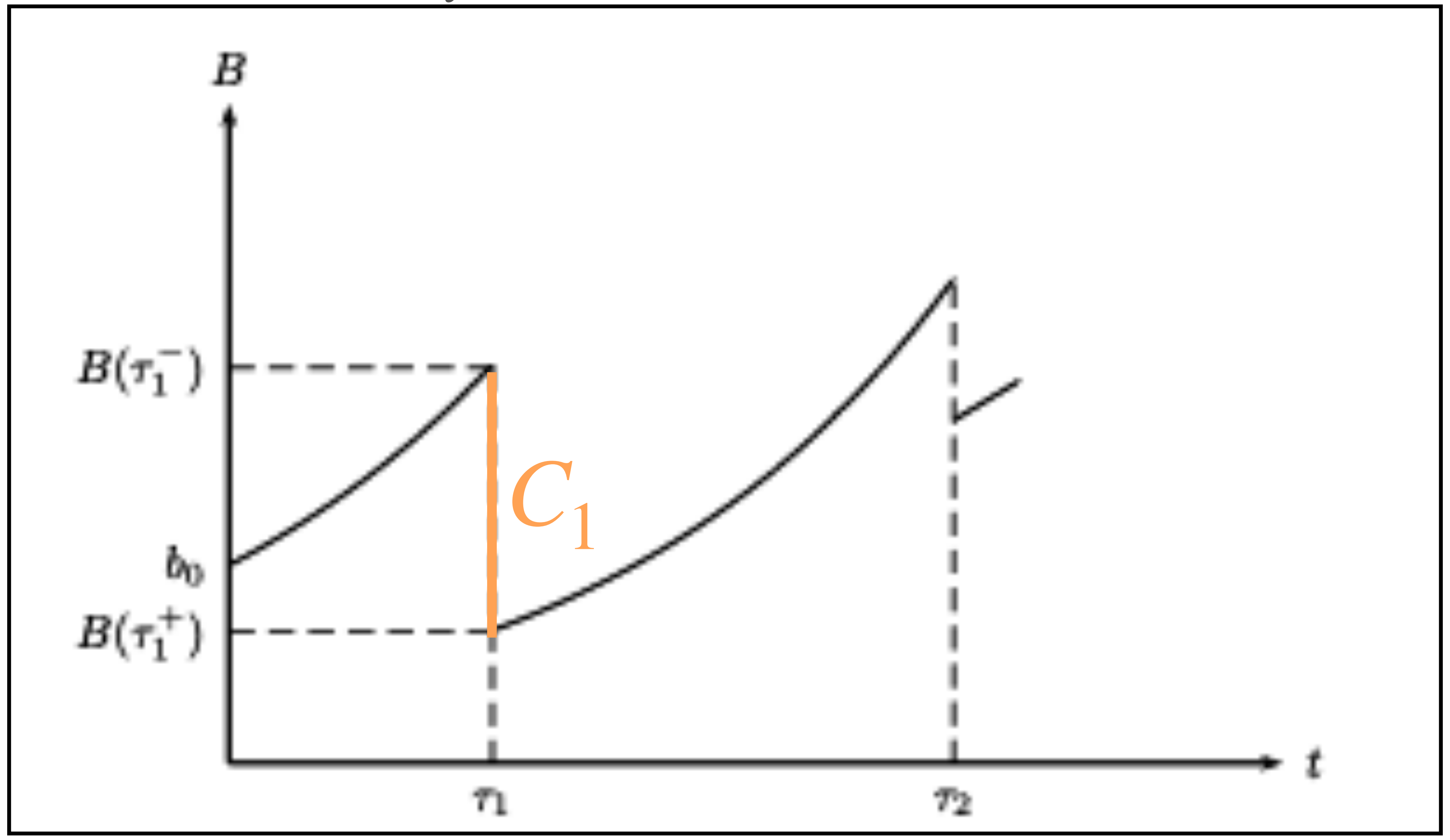
- **The restoration cost** is increasing and convex in the area brought under restoration and decreasing in the lost habitat area that is not restored, similar as in Harstad (2023)

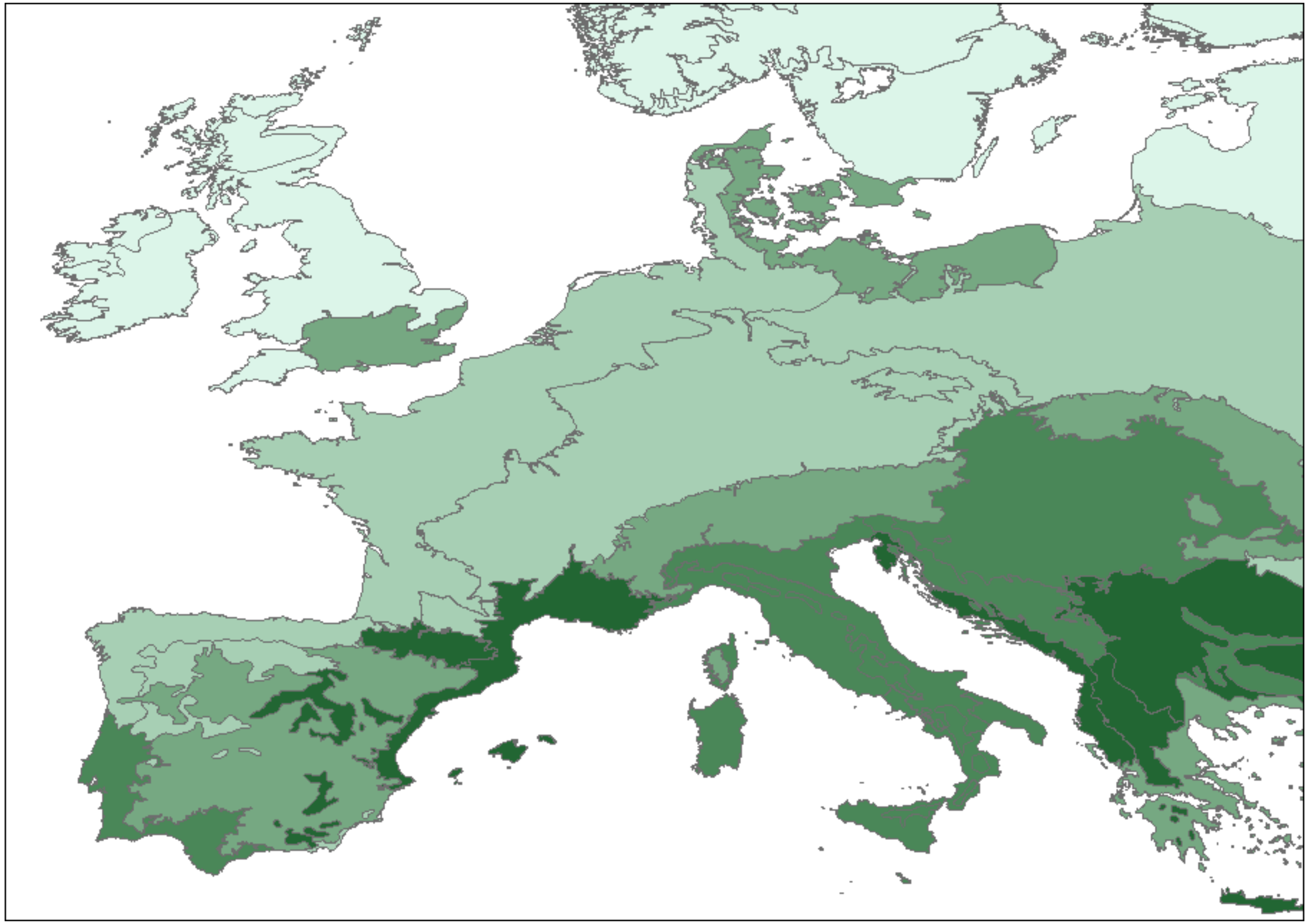
$$C_i(k_i, n_i) = \frac{c_i(k_i\, n_{i,0}\, A_i)^2}{(1-k_i)n_{i,0}A_i} = c_i\, n_{i,0}\, A_i \frac{k_i^2}{1-k_i}$$

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



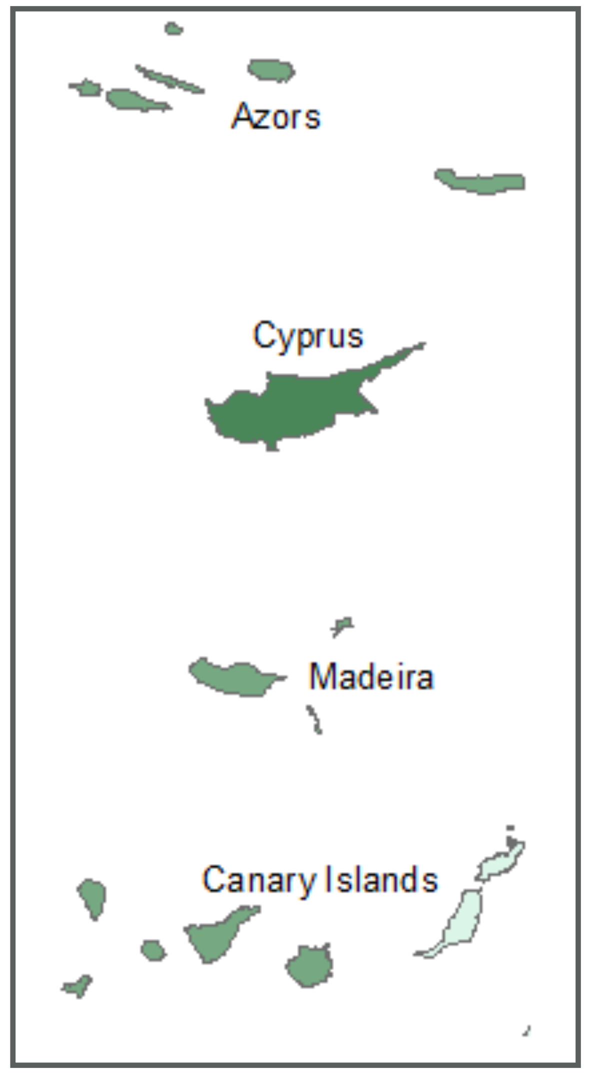




Approximately 8 750 lost species

Largest shares

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



Azores

Cyprus

Madeira

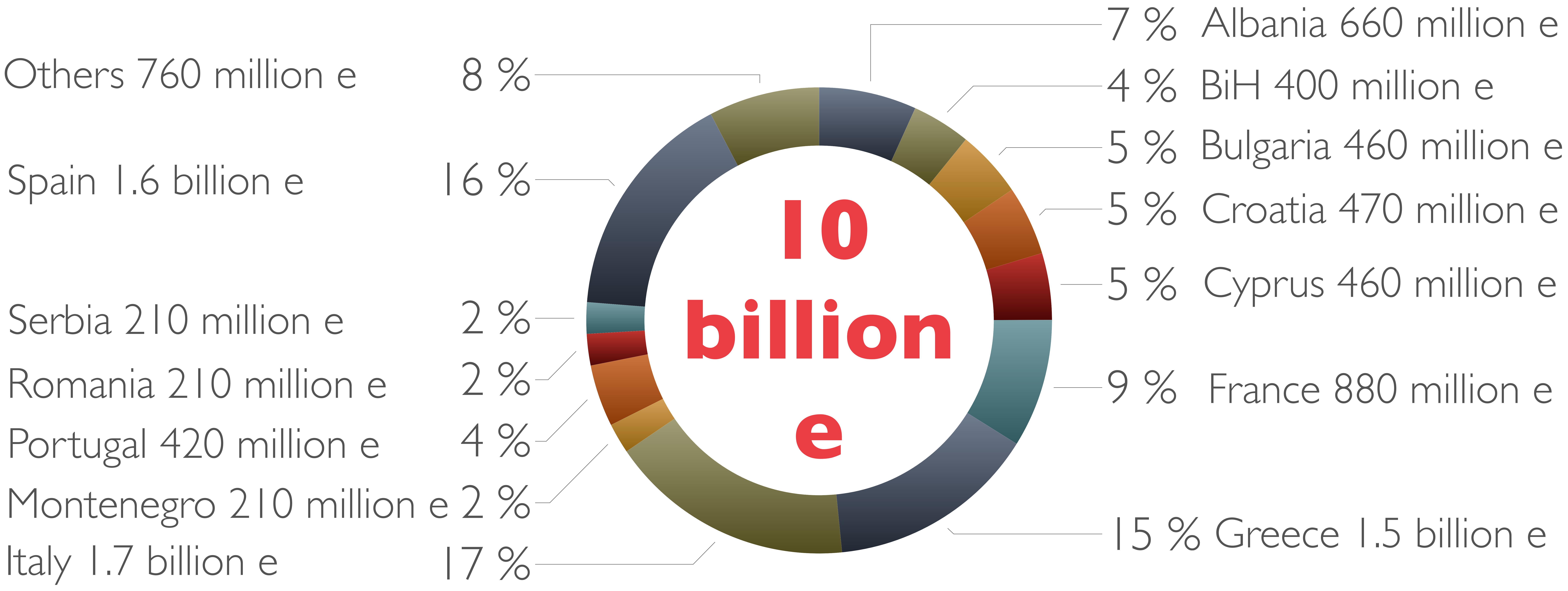
Canary Islands

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

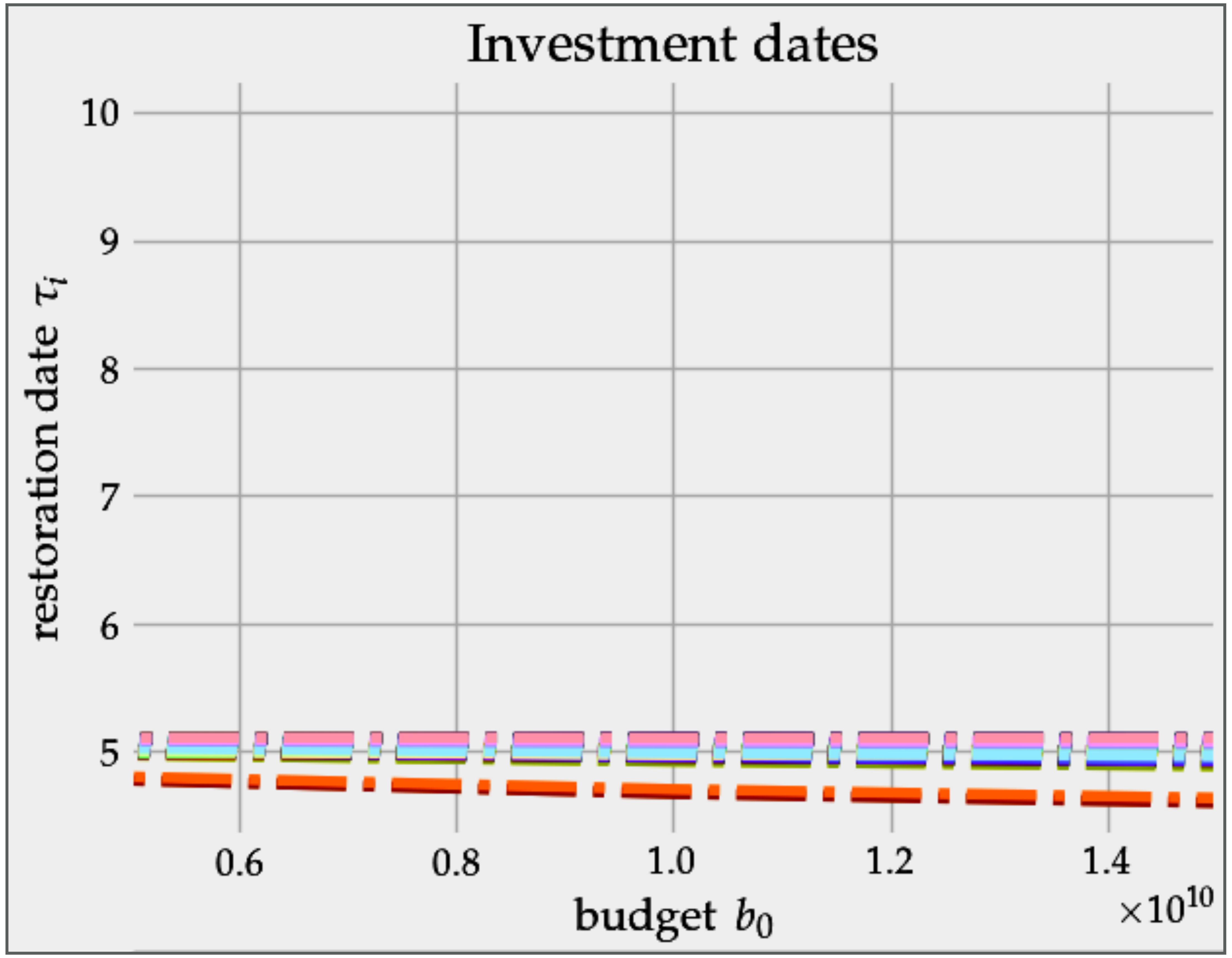
OPTIMAL ALLOCATION OF **10 BILLION E**

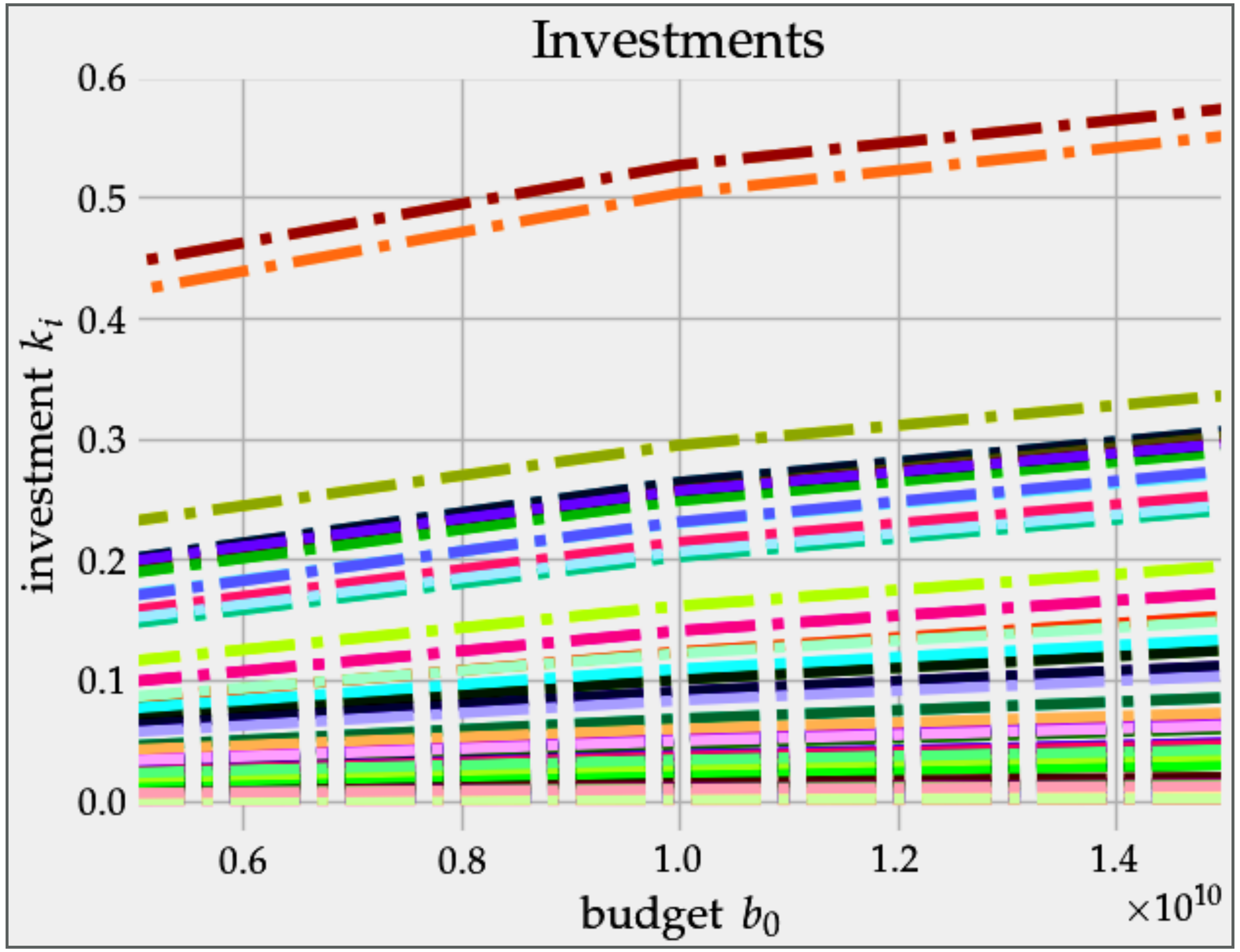
- Allocation is driven by
  1. The number of species 2. The cost 3. The lost habitat before restoration
- large 1, small 2, and large 3 $\Longrightarrow$ money

BUDGET SHARE FOR COUNTRIES



TIMES AND EFFORTS





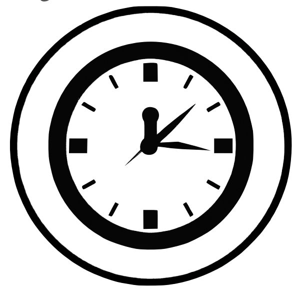
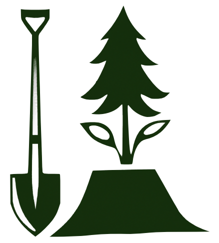
DECISION MAKER'S PROBLEM

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

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

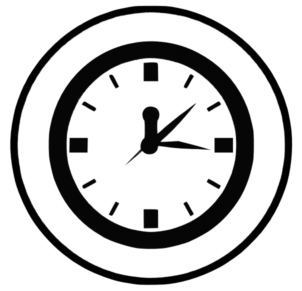
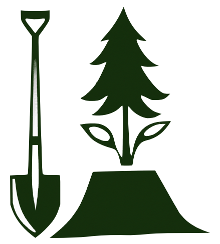
$$B(\tau_i^-) - B(\tau_i^+) = C_i(k_i, N_i(\tau_i))$$

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

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

$\tau_i \geq 0, \quad k_i \geq 0,$ 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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