Multi-Objective Systematic Conservation Planning:

an algorithm based on the epsilon-constraint approach

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1. INTRODUCTION

1. Conservation in a changing world

Global biodiversity is declining rapidly, and the **Kunming–Montreal Global Biodiversity Framework** prioritizes both **conserving genetic diversity** and **expanding protected area networks.**

2. Genetic diversity is multidimensional

Genetic diversity underpins species **persistence** and **adaptive potential**. It comprises **complementary dimensions** that capture different biological processes.

3. Trade-offs are unavoidable

Different spatial distributions create unavoidable trade-offs between genetic diversity dimensions. Conventional **Spatial Conservation planning (SCP)** cannot explicitly evaluate these **trade-offs.**

Two complementary genetic diversity objectives

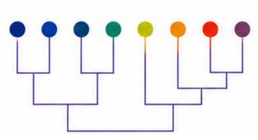
Alpha diversity (within populations)

Nucleotide diversity



Beta diversity (among populations)

Lineages



2. OBJECTIVE

Develop a multi-objective conservation planning framework that generates a transparent Pareto frontier, enabling explicit quantification of trade-offs and identification of balanced conservation solutions between α- and β-genetic diversity.

3. METHODS

Multi-Objective Spatial Conservation Planning (MOSCP)

We formulated a Multi-Objective Spatial Conservation Planning workflow (MOSCP) that uses **epsilon-constraint optimization** to identify optimal **conservation networks** that jointly maximize **nucleotide diversity (α)** and **lineage representation (β)** under a fixed conservation budget.

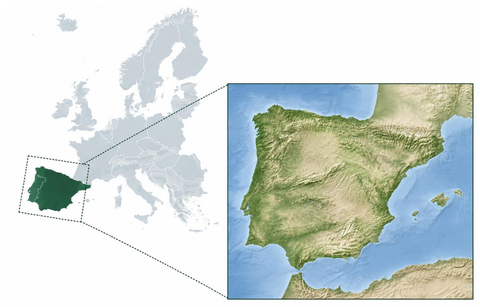
1. Genetic data - Map α (nucleotide diversity) and β (evolutionary lineages) across all species.

2. Conservation targets
Define **how much** α- and β-genetic diversity of each species should be **represented** in the protected area network.

3. Multi-objective optimization - Select planning units that jointly **optimize both objectives** under a fixed conservation budget using the **epsilon-constraint method.**

4. Pareto-optimal solutions - Generate a Pareto frontier of conservation solutions that explicitly characterize **trade-offs** between objectives and identify **balanced conservation solutions.**

Empirical case study



Iberian Peninsula

- 7955 Planning units (10 km resolution)
- 12 amphibian species
- 20 reptile species
- Mapped nucleotide diversity per species
- Mapped lineage distributions per species

4. RESULTS

1. Pareto trade-offs

MOSCP identified a continuous Pareto frontier, demonstrating that maximizing nucleotide diversity and lineage representation requires explicit trade-offs.

2. Alternative optimal conservation networks

Different Pareto-optimal solutions generated distinct spatial prioritizations under the same conservation budget, providing decision-makers with flexibility to accommodate different conservation objectives.

3. Target achievement

Pareto-optimal solutions balanced representation across nucleotide diversity and evolutionary lineages, although some taxa required greater trade-offs than others.

4. Effects of budget

Increasing the conservation budget reduced target shortfalls for both objectives while maintaining the trade-off between nucleotide diversity and lineage representation.

5. Comparison with conventional SCP

Conventional single-objective Spatial Conservation Planning approaches identified only the extreme Pareto solutions, whereas MOSCP approximated the complete Pareto frontier, enabling explicit evaluation of trade-offs between complementary genetic diversity objectives.

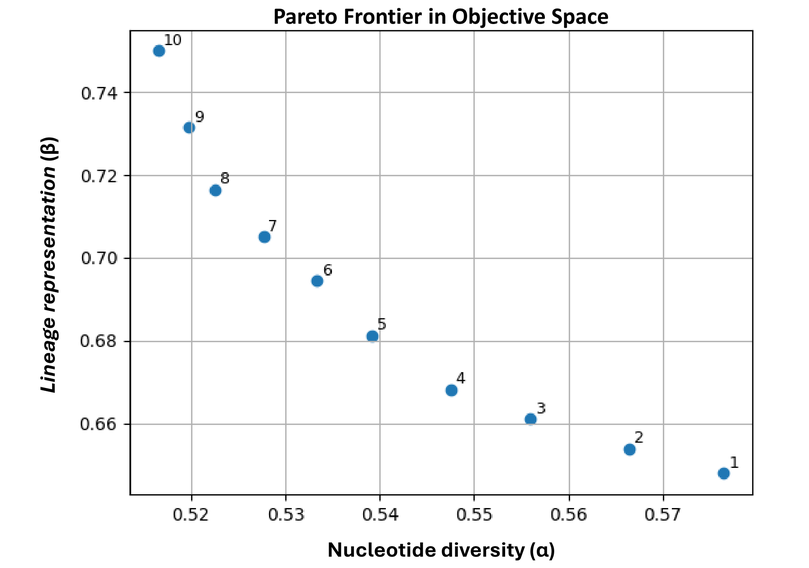


Figure 1 *- Pareto frontier illustrating the trade-off between shortfalls in nucleotide diversity (α) and lineage representation (β) under 20% budget. Each point represents a Pareto-optimal solution.*



Figure 2 - Alternative Pareto-optimal conservation networks for the empirical case study (20% budget). Green = selected planning units; grey = unselected planning units. *Each map corresponds to a different Pareto-optimal solution identified in Figure 1.*

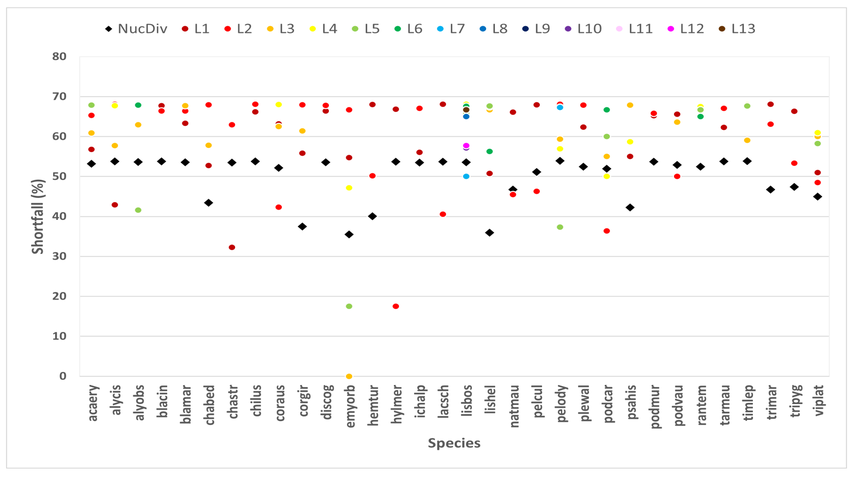


Figure 3 - Species- and lineage-specific target shortfalls for Solution 5 (20% budget). Lower values indicate better target achievement.

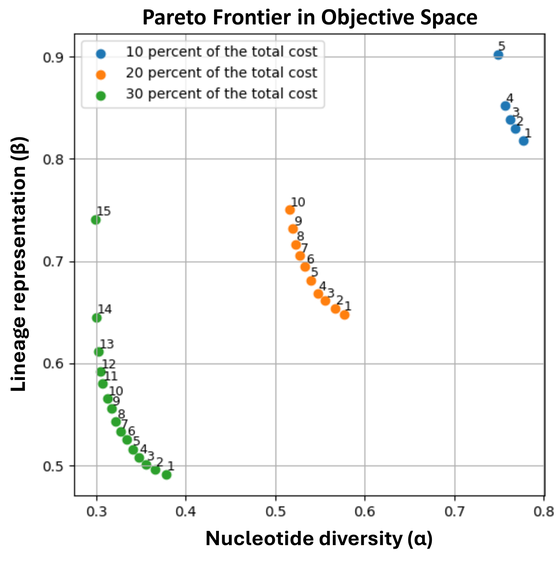


Figure 4 - Pareto frontiers under 10%, 20% and 30% conservation budgets. Increasing the budget reduced shortfalls while maintaining the trade-off between objectives.

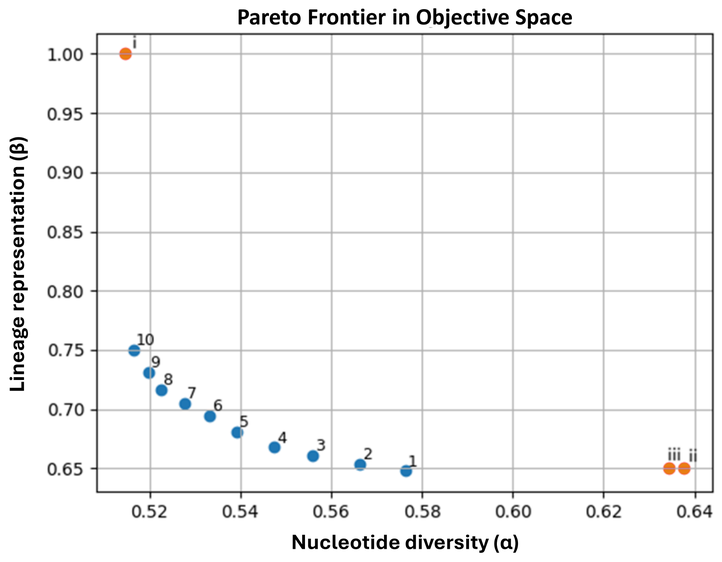


Figure 5 - Comparison of conventional SCP (orange dots) and MOSCP (blue dots). Conventional SCP identifies only the extreme Pareto solutions, whereas MOSCP approximates the complete Pareto frontier.

5. KEY MESSAGES

1.Explicit trade-offs

MOSCP quantifies trade-offs through the Pareto frontier, supporting transparent and evidence-based conservation decision-making.

2.Flexible decision-making

Alternative Pareto-optimal solutions allow conservation networks to be tailored to different budgets and management priorities.

3.Generalizable framework

The framework can be readily extended to conservation planning problems involving competing objectives, including ecosystem services, climate adaptation, food and energy production, and tourism.

6. ACKNOWLEDGEMENTS

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