**Comparing spatial prioritization methods for biodiversity conservation and ecosystem service supply in Europe**

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**Abstract:**

Identifying priority areas that simultaneously supply ecosystem services and are important for biodiversity underlying the supply of ecosystem services is essential for well-informed decision-making on land use and conservation planning. Multiple methods for spatial prioritization of locations supplying individual or multiple ecosystem services, and for the balanced or optimal allocation of biodiversity conservation actions exist, but the benefits and disadvantages of using these methods are seldom explored. Furthermore, the technical complexity, data requirements and the transparency of the method parameterization further make a great difference in the usability of each method in practical work. Here, we compare a simple scoring method, heuristic prioritization software Zonation, and an exact spatial optimization method in prioritizing locations important for multiple ecosystem services and biodiversity at the European scale. Each method is used within a realistic, but hypothetical decision-making context. We show that for very simple analysis types, the scoring-type of approach performs very similarly to Zonation and the exact optimization method. However, more complex - and arguably more policy-relevant - analysis types can only be accommodated by the more complex methods. We demonstrate the practical implications of using each approach in operationalizing the concept ecosystem services and biodiversity conservation planning into more widespread practical use. We argue that the road forward in using planning methods is a combination of technical credibility, decision-making relevance, and effort in opening up the planning process to the stakeholders involved.

**Keywords:** spatial prioritization; ecosystem services; biodiversity conservation; Zonation; optimization; environmental decision-making

**Software and/or data availability:**TBA

# Highlights

* We compare three different spatial prioritization methods of identifying priority locations for both the supply of ecosystem services and biodiversity conservation on European scale.
* The prioritization results show that for a relatively simple prioritization analyses, all the methods perform similarly
* Priority areas for the selected ecosystem services are aggregated to central parts of Europe, whereas biodiversity priorities are found in the Mediterranean basin and Northern Fennoscandia.
* We provide information to guide the selection of a suitable approaches, including methods and the types of data needed, in operationalizing the spatial planning for ecosystem services and biodiversity.
* Importantly, our methods and results can help to characterize and quantify the potential trade-offs between ecosystem services supply and biodiversity conservation.

# 1. Introduction

Ecosystem services, activities or functions of ecosystems that provide benefit (or occasionally disbenefit) to humans (Mace et al., 2012), has quickly risen in popularity in guiding environmental management decisions. Ecosystems are thought to provide a broad spectrum of different services that directly or indirectly contribute to the human well-being on multiple spatiotemporal scales (REFS). Given the strong emphasis placed on ecosystem services especially in the national and international policy arenas (REFS), the operationalization of the concept of ecosystem services is still well underway. Part of this operationalization process is the development of methods and tools for spatial planning that integrates multiple objectives simultaneously in a transparent and cost-effective manner. Spatial planning and spatial support systems are widely studied and used in environmental context in land use, natural resource, urban and conservation planning (REFS). For practical relevance, spatial planning needs to be able to include ecological, economic and social factors relevant for whatever decision-making problem is at hand. Integrating spatial planning with decision-analytical methods has been done under the rubrics such as multi-criteria decision making (REFS), XXX (REFS) and XXX (REFS). Management decisions will increasingly need to account for both biodiversity conservation and the provision of ecosystem services (Goldman and Tallis, 2009) and therefore methods able to quantify the associated trade-offs are urgently needed (Cordingley et al., 2016). It is crucial, however, to be fully aware of the assumptions behind methods used to assess their suitability for the task.

In practice, spatial planning is useful for guiding environmental management only if the planning methods and the information they provide can been embedded into real-life management context. In the field of conservation science, systematic conservation planning (Margules and Pressey, 2000) has been perhaps to most influential framework combining aspects of spatial planning to implementation of biodiversity conservation (Kukkala and Moilanen, 2012). Within this broader decision-analytical framework, the more technical biogeographic-economic assessment of which areas are the most important for biodiversity and when and how particular actions should be implemented to achieving conservation goals, is called spatial conservation prioritization (SCP)(Ferrier and Wintle, 2009; Kukkala and Moilanen, 2012; Wilson et al., 2007). In addition to ecological effectiveness, socio-economic efficiency is a key aspect of SCP: how should limited resources be invested to maximize expected outcomes (the persistence of biodiversity)(Evans et al., 2015). While SCP was originally developed for designing more effective protected area networks, the underlying principles and methods developed based on them are suitable for prioritizing between a suite of different actions (REFS). For example, spatial conservation prioritization has been applied in context of natural resource extraction (Kareksela et al., 2013), habitat restoration (Thomson et al., 2009) and food production (Dobrovolski et al., 2014). Many SCP methods have also been implemented as software tools (REFS), increasing the uptake and usability of the methods and concepts in practice.  
  
Spatial prioritization methods have also been applied to prioritizing areas suitable for the provision of ecosystem services (Chan et al., 2006; Schröter et al., 2014), provision of ecosystem services and urban development (Casalegno et al., 2014) and both provision of ecosystem services and biodiversity conservation (Moilanen et al., 2011; Nin et al., 2016; Reyers et al., 2012). Spatial prioritization of ecosystem services provision is fundamentally different to spatial conservation prioritization of biodiversity, but the two share enough similarities for SCP methods to be useful for management concerning ecosystem services. The basic elements of a prioritization problem are the same for both biodiversity conservation and ecosystem services provision: quantitative and spatial features that need to be protected or secured, potential threats that features are facing, potential actions that can be taken to retain the features and mitigate threats, and information on the costs of the potential actions (Ferrier and Wintle, 2009; Luck et al., 2012). According to Luck et al. (2012), the prioritization of ecosystem services provision must additionally consider at least the availability of alternative meansof providing benefits supplied by services, the capacity of an ecosystem services to meet human demands, and the scaleof, and site dependencyin, the delivery of services. Furthermore, asymptotic benefit-functions often used in SCP (Arponen et al., 2005; Wilson et al., 2009b) are not suitable for all ecosystem services for which either linear or more complex relationships are more appropriate (Barbier et al., 2008; Luck et al., 2012). Emphasizing the relative importance of rare features over more common features (Moilanen et al., 2005; Williams et al., 1996) is another principle which may be more suitable for biodiversity rather than ecosystem services features.

One practical strength of adapting SCP methods in spatial prioritization of ecosystem services supply is that SCP has already seen wide operationalization and adaptation in real-life decision-making (Knight et al., 2009; Lehtomäki and Moilanen, 2013). Based on experiences from a broad array of applied projects and the existing literature on the applicability of methods and tools to practice, it is possible to assess the potential of SCP methods in the context of ecosystem services. In the broader context of providing decision-support tools capable of dealing with ecosystem services, there are multiple good reviews available assessing the technical and practical aspects of different software tools (e.g. Bagstad et al., 2013; Langemeyer et al., 2016). However, only few assessments explicitly consider explicitly consider spatial methods and combining both ecosystem provision and biodiversity conservation simultaneously.

A broad set of methods with variable complexity and flexibility are available for spatial prioritization. Relatively simple methods that sum the occurrence of biodiversity features (e.g. species) in a given area of interest have been popular exactly because of the simplicity of the approach (REFS). However, since most of these so-called “scoring” methods do not take into account complementarity, […], solutions produced are inefficient (Wilson et al., 2009a). Spatial conservation prioritization problems concerning the selection of an optimal set of areas based on some selection criteria are also solvable exactly using spatial optimization techniques such as integer linear programming (ILP) (Beyer et al., 2016). The advantage of ILP methods is that they produce a truly optimal solution or a quantitative estimate on the sub-optimality of the solution. The downside is that accounting for all the factors relevant for real-life prioritization problems quickly renders the optimization computationally infeasible (REFS), or require simplifications reducing the relevance of the solution (Moilanen, 2008). This is why heuristic methods have proven to be popular in spatial conservation prioritization: they are flexible enough to accommodate factors relevant for decision-making while retaining computational tractability (Moilanen and Ball, 2009). They cannot, however, guarantee the optimality of the solution and are typically on the same level of technical complexity as exact optimization methods.

Here, we compare three spatial prioritization methods that fall into the three categories of methods described above: rarity-weighted richness (RWR, scoring method), Zonation (heuristic), and ILP approach (exact optimization). We apply each of the methods on a prioritization problem constituting of 11 features describing ecosystem services capacity and 759 features of estimated extents of occurrence of tetrapods (amphibians, birds, mammal and reptiles) on European scale. While the prioritization results are indicative of true priority areas, we are more interested in the assumptions one needs to make in order to use each method, and the relative differences between the methods. This work contributes to the understanding of operational requirements of spatial planning integrating ecosystem services and biodiversity conservation, as well as developing operational instruments for such planning. We are interested in how the different methods used to identify important areas for ecosystem services and biodiversity are suited for operational planning and provide guidelines for doing so.

# 2. Material and methods

## 2.1 Datasets

* We use 11 features of ecosystem services capacity (group name: ES) and 759 features of biodiversity features (group name: BD). All datasets (n=770, group name: ALL) have originally been developed for different purposes, for a more detailed description of the data please refer to the original sources given in [Table 1](https://docs.google.com/spreadsheets/d/1niV9Oe8pavgskiq0ibMzPt6F_oJU3uTD3R2pY7RwyDU/edit#gid=0).
  + Our study area covers 26 EU member states (EU28 without Cyprus and Malta, **Figure 1**)
    - Countries involved were selected on data availability and EU membership.
  + **Table 1**: Datasets used in the analyses
    - [Working version](https://docs.google.com/spreadsheets/d/1niV9Oe8pavgskiq0ibMzPt6F_oJU3uTD3R2pY7RwyDU/edit?usp=sharing)
    - BD data into a supplementary Table S1
  + The temporal coverage of the data varies from X to Y.
  + Ecosystem services data packaged for PROVIDE/VOLANTE project.
  + NUTS2 regions downloaded from Eurotstat.



Figure 1. Area of interest spanning 26 EU Member States.

Table 1

Table 1. Datasets used in the analysis.

## 2.2 Methods

* Data pre-processing
  + All data either originally in 1x1 km resolution, or rasterized into a common grid.
  + All data warped and/or projected into ETRS-LAEA (EPSG:3035) with matching extents.
  + We apply an occurrence level normalization on all datasets: each cell value is divided by the sum of all cell values. After the operation, the value in each cell will give the fraction of the overall occurrence level of that cell (i.e. values over all cells sum up to 1.0).
  + Data pre-processing implementation done with Python GDAL bindings (packages: NumPy, Scipy, rasterio).
* Prioritization methods
  + Three methods:
    1. Scoring (rarity-weighted richness, RWR)
       - Albuquerque and Beier (2015)
       - Note that this is slightly modified version of the original, which is based on presence/absence data, in which cells can only have a value of {0, 1}.
    2. Zonation (ZON)
       - Moilanen et al. (2014)
       - Cell-removal rule: additive benefit function.
    3. Exact optimization (ILP)
       - Beyer et al. (2016)
       - Using proprietary Gurobi solver
       - The hierarchical rank priority map is produced by solving maximum coverage problems with multiple area targets.
  + For implementation details, see **Figure S2**.
  + Weighting scheme used: the same aggregate weights assigned to all ES features and all BD features.
  + For each method, we created the following variants: All features (ALL, n=770), just ecosystem services (ES, n=11) and just biodiversity features (n=759).

## 2.3 Results comparison

* We aggregate all the prioritization results on NUTS2 regions.
* Quantitative comparisons between A) methods and B) datasets (ALL, ES, BD).
  + Jaccard’s index for the best 10% and worst 10% (**Table 2**)
  + Kendall’s Tau rank correlation (**Table 2**)
  + Map Comparison Statistic (MCS) (NUTS2 results) (**Table 2**)
  + Deviation from optimal solution (as given by the ILP) (**Figure 3**)

Table 2

Table 2. Spatial similarity/dissimilarity between different methods and dataset. Sub-table A give Jaccard’s similarity index between the best and worst 10% of the solution, sub-table B shows the Kendall’s Tau correlation coefficient between the solutions, and C gives the average map comparison statistic between NUTS2 units.

* Qualitative method comparison. Bagstad et al. (2013) provide a useful set of criteria against which methods and software tools can be assessed.
  + The fit of the underlying assumption/concepts with topic and research question
  + Quantification and uncertainty
  + Time requirements
  + Capacity for independent application
  + Level of development and documentation
  + Scalability
  + Generalizability
  + Nonmonetary and cultural perspectives
  + Affordability, insights, integration with existing environmental assessment

# 3. Results

## 3.1 Spatial patterns and similarity

* **Figure 2**: Prioritization rank maps for ALL variants (9 panels: 3 methods x 3 variants [ALL, ES, BD] by NUTS2 aggregations)
* **Table 2**: Similarity dissimilarity between the complete set of analysis variants (ALL + ES + BD) as measured by A) Jaccard’s index, B) Kendall’s Tau rank correlation, and c) MCS.

## 3.2 Solution performance and optimality

* **Figure 3:** Solution performance comparison. Performance curves for ALL, ES and BD plotted based on the removal order given by ILP\_ALL, ILP\_ES and ILP\_BD.

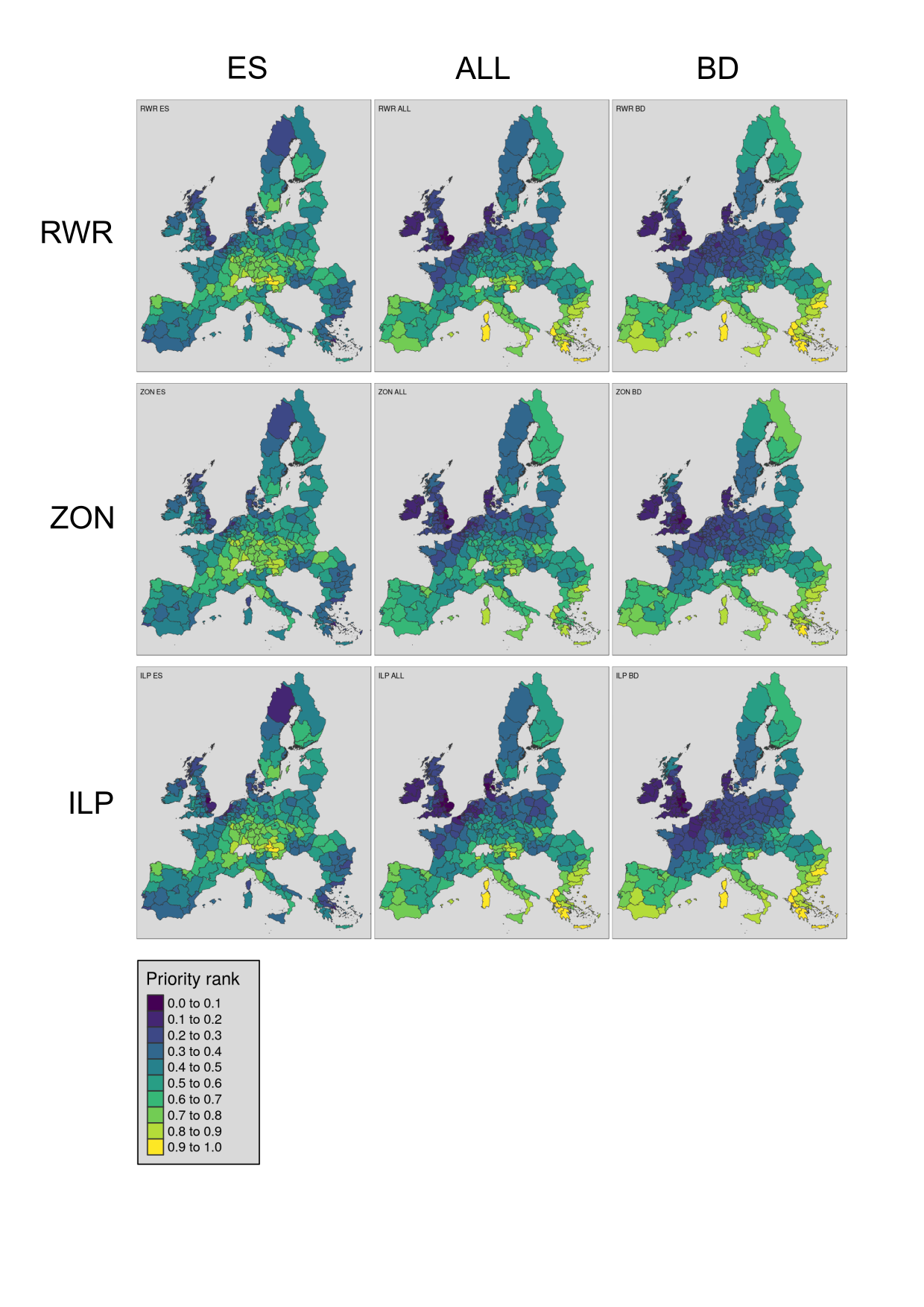


Figure 2. Rank priority maps for different methods (RWR, ZON and ILP) in columns, and for different datasets in rows (ALL, ES, BD).

FIG 3

Figure 3. Performance curves for RWR\_ALL (A), ZON\_ALL (B) and ILP\_ALL (C). XX curve is an average over all features, YY and ZZ are groups average for ES and BD respectively. Panel D show the average representation of features in RWR and ZON solutions when the rank order is taken from ILP (since it is guaranteed optimal).

# 4. Discussion

## 4.1 Method performance

* Our results show that for a very simple type of prioritization problems, the more complex methods (ZON and ILP) do not produce significantly better results than the simpler scoring method (RWR). However, this is not very surprising given that all the algorithms are similar in their function.
* However, for more complex problems which most conservation prioritization problems typically are (Moilanen, 2008) , more complex methods are needed. This is particularly true if we aim at prioritizing actions instead of places as more complicated factors (costs, willingness to participate etc) must be accounted for.
  + RWR cannot be extended for example to account for connectivity and costs in a realistic manner
  + Zonation can do this
  + ILP could be implemented, particularly given the recent improvements both in software and hardware [(Beyer et al. 2016)](https://paperpile.com/c/Pgo1r9/2lNp).

## 4.2 Selecting the right tool

* Many prioritization methods designed with biodiversity features in mind give high emphasis on relative rarity of features. Furthermore, ways of accounting for spatial arrangement of features are predominantly done with the ecology of species mind (e.g. ecological connectivity).
* The extent to which spatial prioritization methods and tools are applicable also to the prioritization of areas important for the supply of ecosystem services depends on multiple factors. First, many spatial conservation prioritization methods have been developed primarily with biodiversity in mind (Wilson et al., 2009a). Some key features any many prioritization methods, such as placing higher value on rare features (Arponen et al., 2005) or ecological connectivity (Rudnick et al., 2012), do not necessarily make sense in context of ecosystem services.
* Ecosystem services require additional considerations (e.g. the availability of alternative meansof providing benefits supplied by services, human demand, and the scaleof, and site dependencyin, the delivery of services), which can be considerably different to those of species. In terms of selecting the suitable prioritization tool for the job, we recommend the following:
  1. Study the assumptions behind the tools you are about to use. Is it geared more towards species or ES?
  2. Embrace flexibility, but avoid complexity.

## 4.3 Integrated prioritization of biodiversity conservation and ecosystem services supply

* Trade-offs between ecosystem service provision and biodiversity conservation are most likely common. It does not necessarily follow that priority areas for the provision of ecosystem services are automatically priority areas also for biodiversity (Anderson et al., 2009; Thomas et al., 2012).
* In still remains unclear how exactly ecosystem services should best be incorporated into prioritization schemes that have been developed with biodiversity conservation in mind.
  + Complicating factors
    - Spatiotemporal scales
    - Supply/demand
    - Places/actions
* In addition to quantifying the differences between the different spatial prioritization methods, we also present the full implementation of the analysis that can be adjusted to other types of data.
* Operationalizing ecosystem services requires institutional adaptation, case-specific tailoring of methods, and deliberation among practitioners and stakeholders (Rinne and Primmer, 2015).

# 5. Conclusions

# 6. Acknowledgements

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* Beyer et al. (2016) for making the ILP implementation available.

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# 8. Supplementary information

**Figure S1:** Schematics of the processing steps for each method.

Table S1: Biodiversity features (n=759) used in the analyses.