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YOUNG VOICES AND VISIONS FOR THE UN DECADE OF RESTORATION

PRACTICE AND TECHNICAL ARTICLE

restoptr: an R package for ecological restoration planning

Dimitri Justeau-Allaire^{1,2} , Jeffrey O. Hanson³, Guillaume Lannuzel⁴, Philippe Vismara^{5,6}, Xavier Lorca⁷, Philippe Birnbaum^{1,8,9}

Ecological restoration is essential to curb the decline of biodiversity and ecosystems worldwide. Since the resources available for restoration are limited, restoration efforts must be cost-effective to achieve conservation outcomes. Although decision support tools are available to aid in the design of protected areas, little progress has been made to provide such tools for restoration efforts. Here, we introduce the *restoptr* R package, a decision support tool designed to identify priority areas for ecological restoration. It uses constraint programming—an artificial intelligence technique—to identify optimal plans given ecological and socioeconomic constraints. Critically, it can identify strategic locations to enhance connectivity and reduce fragmentation across a broader landscape using complex landscape metrics. We illustrate its usage with a case study in New Caledonia. By applying this tool, we identified priority areas for restoration that could reverse forest fragmentation induced by mining activities in a specific area. We also found that relatively small investments could deliver large returns to restore connectivity. The *restoptr* R package is a free and open-source decision support tool available on the Comprehensive R Archive Network (<https://cran.r-project.org/package=restoptr>).

Key words: connectivity, constraint programming, ecological restoration planning, fragmentation, landscape indices, R package, systematic conservation planning, wildlife corridors

Implications for Practice

- Strategic and efficient planning is a critical step in achieving global restoration goals.
- Although decision-support tools are available to guide conservation efforts, they are not well suited to ecological restoration, where the underlying issues differ from conservation planning.
- Decision support tools must be flexible and expressive. They also need to consider socioeconomic issues to facilitate a constructive dialogue with stakeholders.
- Open-source and community-based tools have an important role in the UN decade of restoration as they ensure transparency and reproducibility.
- The *restoptr* R package is provided as a flexible, expressive, extensible, free, and open-source tool specifically designed for ecological restoration planning. It can address various challenges, such as restoring connectivity across a fragmented landscape while accounting for socioeconomic issues.

Introduction

Ecological restoration is urgently needed to halt biodiversity declines (Strassburg et al. 2020). Indeed, anthropogenically driven land use threatens species globally, through habitat

destruction, degradation, and fragmentation (Taylor et al. 1993; Díaz et al. 2020). Restoration efforts can potentially revitalize species' habitats, repair connections between habitats, and replenish ecosystem services (Montoya et al. 2012). However, efficient restoration programs must build upon relevant ecological targets considering the previous states of the study areas and their

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specificities. They are also complicated by the fact that restoration efforts must balance intricate ecological objectives with socioeconomic constraints (Margules & Pressey 2000). As such, there has been a growing interest in priority areas for restoration (Adame et al. 2015; Strassburg et al. 2020; Ladouceur et al. 2022). However, unlike protected area design, little progress has been made to provide decision support tools to help plan restoration efforts.

Although conservation planning decision support tools have been applied to ecological restoration, they were not designed for this purpose and might fail to achieve important objectives for ecological restoration planning. For example, decision support tools designed to inform protected areas establishments—such as Marxan (Ball et al. 2009), Zonation (Moilanen et al. 2009), or the *prioritizr* R package (Hanson et al. 2022)—are not well suited for restoration objectives, such as improving overall habitat quality, reducing habitat fragmentation, or restoring ecological connectivity. Indeed, these tools are primarily focused on ensuring adequate representation of species and ecosystems within protected area networks (Margules & Pressey 2000). Although these tools can also promote some degree of connectivity, they only do it through simple metrics, at the protected area scale (Daigle et al. 2020). As such, conservation planning tools have limited ability to identify degraded areas, possibly of low interest for biodiversity conservation but with high potential for ecosystem restoration. Indeed, this potential is, in the vast majority of cases, related to the landscape context, which means that restoration planning must take into account the potential long-term contribution of specific areas at the landscape scale, using appropriate landscape metrics (Bell et al. 1997; de Souza et al. 2013).

To the best of our knowledge, ecological restoration planning lacks a purpose-built decision support tool able to identify priority areas for restoration taking into account both the potential contribution at the landscape scale and socioeconomic constraints. Ideally, such tools should be able to (i) accommodate complex and nonlinear landscape metrics, (ii) provide guarantees on solution quality to ensure cost-efficiency, and (iii) provide an expressive and flexible interface to address a wide variety of problems. Although Justeau-Allaire et al. (2021) recently demonstrated that constraint programming (CP)—a constrained optimization framework based on artificial intelligence (Rossi et al. 2006; Freuder 2018)—has the potential to meet all of these criteria, this framework remains largely inaccessible to restoration scientists and practitioners because it requires specialized expertise.

Here, we introduce the *restoptr* R package, a new decision support tool that relies on CP to provide a generic and user-friendly framework for restoration planning. By leveraging geospatial land cover data (raster or vector) as input data, it offers a wide catalogue of objective functions and constraints that can be composed to formulate various problems. It also provides automated routines for data preprocessing to guarantee data integrity and reduce run time. To showcase its usage, we provide a case study based in the Mount Kaala area, in New Caledonia. Based on aerial

images from 1976, we identified cost-effective restoration areas to reverse the forest fragmentation induced by mining activities between 1976 and 2021. We believe that *restoptr* will be an asset for informing ecological restoration projects worldwide and achieving the Bonn challenge, which aims to restore 350 million hectares of degraded landscapes by 2030.

Methods

Package Overview

The *restoptr* R package provides an expressive, flexible, and extensible framework to address a wide range of ecological restoration planning problems. To achieve this, the package generalizes and extends the methodology originally proposed in Justeau-Allaire et al. (2021). Specifically, it provides an automated preprocessing toolchain to prepare input data for optimization, and it also provides a user-friendly application programming interface (API) which is extensively documented with many examples available online (<https://dimitri-justeau.github.io/restoptr/>). After the user has supplied geospatial land cover data and specified a problem formulation, the package can identify priority areas for restoration. These priority areas satisfy constraints and are guaranteed to be optimal (or near-optimal) for the optimization objective. Several parameters are available to configure the solving process, such as the number of alternative solutions that must be identified, the solving time limit, and the optimality gap (allowed distance to the optimal value). For performances reasons, the solving process is delegated to *restopt*, a dedicated Java library which relies upon the Choco CP solver (Prud'homme & Fages 2022). The communication between R and Java is handled by the *rJava* R package (Urbanek 2021). The workflow implemented by *restoptr* is illustrated in Figure 1.

Automated Data Preprocessing Toolchain

Preparing geospatial data for spatial combinatorial optimization problems, such as restoration planning ones, is prone to errors. Indeed, when several datasets are used, it is necessary to ensure that they have the same geographic coordinate system and the same resolution. In particular, since the solving time of such problems is highly dependent on spatial resolution, it is often necessary to resample the datasets to obtain a resolution that offers a compromise between accuracy and performance. To support users in this process, we implemented an automated data preprocessing toolchain that substantially reduces the risk of errors in data preparation, but also makes the entire processing chain more flexible and easier to use. Based on the *terra* R package (Hijmans et al. 2022), the toolchain needs a binary habitat raster, which can be at any resolution, and optionally a raster or vector representing areas that are either available or locked out for ecological restoration. Two parameters are also needed: (i) the *aggregation factor* which indicates the size of the planning units relative to the input habitat resolution and (ii) the *habitat threshold* which indicates the minimum required

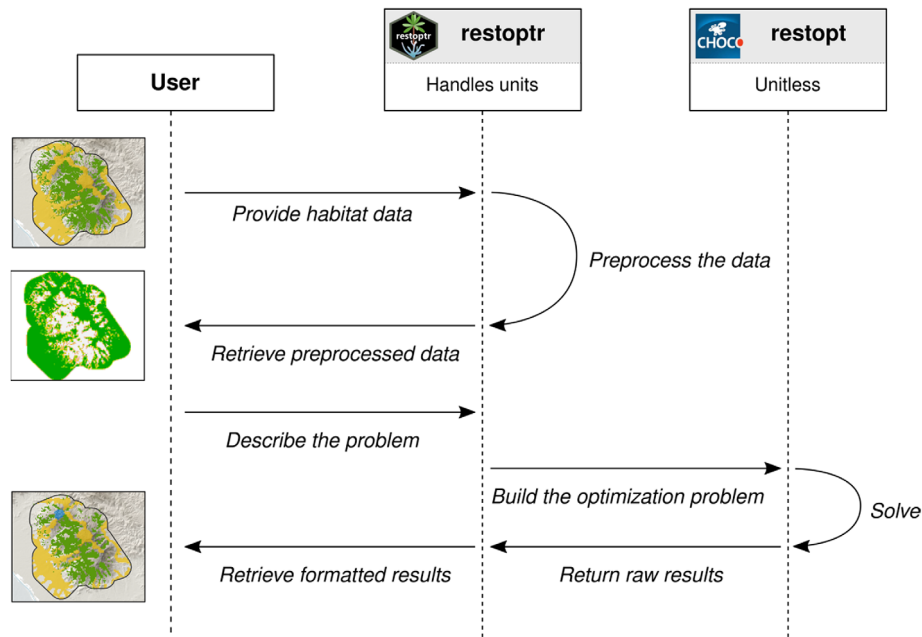


Figure 1. Sequence diagram representing the interactions between the user and *restoptr* in a regular workflow. The vertical dashed line, from top to bottom, represents the chronological sequence. First, the user provides raster habitat data, which is preprocessed by *restoptr*. Then, the user describes its restoration planning problem through the R API. This problem is translated into a constrained optimization problem, which is solved by *restopt*, the Java optimization engine based on Choco-solver (Prud'homme & Fages 2022). By relying on the *units* R package (Pebesma et al. 2016), the R API, *restoptr* handle several distances and surface units whereas *restopt* only handles cell surfaces.

proportion of habitat within a planning unit to consider it as habitat. The preprocessed data consist of a set of rasters having a resolution equal to the input habitat raster divided by the aggregation factor. The most important outputs of the preprocessing toolchain are as follows:

- The existing habitat raster is a binary raster, indicating which planning units are habitat. Only planning units containing a proportion greater or equal to the habitat threshold parameter are considered habitat. For example, if the aggregation factor is 2 and the habitat threshold is 0.75, then the planning units are composed of 2×2 cells from the input habitat raster, and only planning units containing at least three habitat cells are defined as habitat planning units.
- The restorable habitat raster is a quantitative raster which describes for each planning unit the number of cells from the input habitat raster that is not habitat, that is, the restorable area within each planning unit.

Problem Formulation

Let S be a landscape composed of n planning units: $\{x_0, \dots, x_{n-1}\}$. According to input habitat data and users' parameters, each planning unit is either habitat ($x_i = 0$) or non-habitat ($x_i = 1$). We denote the set of habitat planning units by S_h and the set of non-habitat planning units by S_d . Let $f[S_h] : \mathcal{P}(S_d) \mapsto \mathbb{R}$ be a configurable objective function that takes a set of non-habitat planning units as input and returns a number ($\mathcal{P}(S_d)$ is the power set of S_d , that is, the set of all subsets of S_d).

The configurable objective function $f[S_h]$ evaluates the outcome of restoring a set of non-habitat planning units, taking into account its contribution to the whole landscape. The *restoptr* framework addresses ecological restoration planning problems expressed in the following form: given a set of constraints C , find $R \in \mathcal{P}(S_d)$ maximizing (or minimizing) $f[S_h]$ such that all constraints in C are satisfied. Note that there can be several solutions to a single problem. It is also possible to relax the optimization objective with an optimality gap.

As expressed, this constrained optimization problem offers a high degree of liberty to users through the choice of the constraints and the optimization objective. The *restoptr* framework includes several constraints that can represent either ecological or socioeconomic targets, and allows to set various optimization objectives (see Table 1). For example, it is possible to limit the spatial extent of restoration efforts using `add_compactness_constraint()`, which can help ensure their cost-efficiency by integrating economies of scale. In addition, `add_connected_constraint()` or `add_components_constraint()` can be used to restrict the restoration area to be spatially contiguous or to be composed of a controlled number of spatially contiguous areas. On the other hand, `add_restorable_constraint()` can be used to set minimum restoration goals or to define a maximum budget. To meet ecological connectivity restoration targets, `add_min_iic_constraint()` or `set_max_iic_objective()` can be used to respectively set a minimum value for the integral index of connectivity or maximize it (Pascual-Hortal & Saura 2006). When the aim is to minimize the total cost of the

Table 1. Functions available in the *restoptr* package for specifying constraints and objectives. These functions can be combined to identify priority areas that meet particular criteria or optimize a particular metric.

Name	Description
Constraints	
<code>add_available_area_constraint</code>	Specifies that only certain planning units are available for restoration.
<code>add_compactness_constraint</code>	Specifies the compactness of the selected planning units, which is defined as the diameter of the smallest enclosing circle.
<code>add_components_constraint</code>	Specifies the number of connected components of the solution (i.e. number of spatially continuous areas).
<code>add_connected_constraint</code>	Ensures that all the selected planning units are connected (i.e. spatially continuous).
<code>add_locked_out_constraint</code>	Specifies that certain planning units cannot be selected for restoration.
<code>add_min_iic_constraint</code>	Specifies a minimum target value for the integral index of connectivity (Pascual-Hortal & Saura 2006) after restoration.
<code>add_min_mesh_constraint</code>	Specifies a minimum target value for the effective mesh size (Jaeger 2000) after restoration.
<code>add_restorable_constraint</code>	Specifies the available amount of surface for restoration. This constraint can both enforce the minimum and the maximum area to restore.
Optimization objectives	
<code>set_max_iic_objective</code>	Maximize the integral index of connectivity.
<code>set_max_mesh_objective</code>	Maximize the effective mesh size.
<code>set_max_nb_pus_objective</code>	Maximize the number of selected planning units.
<code>set_max_restore_objective</code>	Maximize the amount of restoration area.
<code>set_min_nb_pus_objective</code>	Minimize the number of selected planning units.
<code>set_min_restore_objective</code>	Minimize the amount of restoration area.
<code>set_no_objective</code>	Only satisfy the constraints.

restoration project, `set_min_nb_pus_objective()` or `set_min_restore_objective()` can be used to respectively minimize the number of planning units selected for restoration or the total amount of area to restore within the selected planning units.

Restoptr R API in a Nutshell

We designed the API of the *restoptr* R package based on three key principles: *ease of use*, *flexibility*, and *extensibility*. To initialize a new problem, the `restopt_problem()` R function is used with the following inputs: (i) a habitat raster (in the form of a *terra* raster object), (ii) an aggregation factor, and (iii) a habitat threshold (as described earlier). For example, with a *terra* raster object named `habitat`, an aggregation factor of 2, and a habitat threshold of 0.75, a `restopt_problem()` object can be created as follows:

```
> problem <- restoptr_problem
(habitat, 2, 0.75)
```

This problem object contains all the preprocessed data. If needed, this data can be accessed from the object. For example, the restorable area data can be plotted using the following command:

```
> plot(get_restorable_area(problem))
```

This problem can then be tailored by adding constraints and an optimization objective. To provide a concise API, the pipe operator `%>%` of the *magrittr* R package can be used (Bache et al. 2022). For example, adding a connectivity constraint can be added as follows:

```
> problem <- problem %>%
add_connected_constraint()
```

If for certain reasons some areas are not available for restoration (e.g. private land), it is possible to use the `add_locked_out()` function with geospatial (raster or vector) data indicating these forbidden areas:

```
> problem <- problem %>%
add_locked_out_constraint(locked_out)
```

A similar procedure is used to specify the optimization objective. For example, to specify the maximization of the effective mesh size (Jaeger 2000) as the optimization objective:

```
> problem <- problem %>% set_max_mesh()
```

The optimization process can also be customized with settings. It is possible to configure the number of solutions to output, the time limit, or an optimality gap. For example, the following code can be used to specify that, if possible, 50 solutions should be obtained:

```
> problem <- problem %>% add_settings
(nb_solutions = 50)
```

Finally, once the problem is well defined, the `solve()` function can be used to start the solver and retrieve solutions:

```
> solutions <- solve(problem)
```


The `solve()` function outputs information on which areas are identified as priority areas. If only a single solution is returned, then the function will output a `restopt_solution` object, and if multiple solutions are returned, then a list of these objects is returned. Specifically, a `restopt_solution` object is an extended version of the terra R package raster format that contains additional metadata pertaining to the optimization process. These metadata can be accessed using the `get_metadata()` function.

Solving Procedure

Once a restoration planning problem has been described, the `solve()` function relies on the *rJava* R package (Urbanek 2021) to translate the `restopt_problem()` object into a constrained optimization problem using the *restopt* Java library (Justeau-Allaire 2022). This library is dedicated to the solving procedure and relies on Choco-solver, a state-of-the-art CP library (Prud'homme & Fages 2022). When the solving process is complete, the solutions are sent back to the R session, and *restopt* converts them into raster, including metadata about the solutions' quality and characteristics. Compared with the original approach, we substantially improved the solving performances and memory footprint by rewriting the model and relying on global domain views, a new CP technique well suited to restoration planning problems that rely on set and graph variables (Justeau-Allaire & Prud'homme 2022). As an example, using the same computing server (Ubuntu, Intel Xeon E5-2620 CPU 2.40GHz \times 12, 64 GB RAM), preliminary analysis indicate that our new model is approximately 7.4 times faster on the « Côte Oublie » case study (Justeau-Allaire et al. 2021; Justeau-Allaire & Prud'homme 2022).

Case Study

In New Caledonia, many vegetation areas are threatened by mining activity, which is the pillar of the archipelago's economy. However, mining companies have a legal obligation to invest in the ecological restoration of their operating areas.

To ensure that this obligation is efficiently fulfilled, it is essential to inform both local authorities and mining companies of ecological restoration plans that are both cost-efficient and ecologically relevant. To help achieve this, historical landscape data can play an important role to assess habitat loss and changes in landscape patterns. In particular, such data can be used to define relevant ecological restoration targets based on the past state of a landscape. In this case study, we showcase the usage of the *restopt* R package by identifying reforestation plans in a mining area located in the north of the main island of New Caledonia: the Mount Kaala area (see Supplement S1 for R source code).

Our study area includes all mining concessions in the Mount Kaala area and a 1,000 m buffer zone. In this area, aerial images from 1976 and 2021 are freely distributed by the Government of New Caledonia (see Fig. 2). Forest areas in 1976 were digitized manually, and forest areas in 2021 were digitized using an automated method based on the historical analysis of temporal series from Landsat data (Vancutsem et al. 2021), both at a resolution of 30 m \times 30 m (see Fig. 3). The comparison of forest areas between 1976 and 2021 shows that the area has suffered from forest loss and increased fragmentation. Using the *landscapemetrics* R package (Hesselbarth et al. 2019), we measured the evolution of forest cover and forest fragmentation (see Table 2), the latter measured with the effective mesh size (Jaeger 2000). Then, we formulated a *restopt* problem using an aggregation factor of 3, which corresponds to planning units of 90 m \times 90 m, and a habitat threshold of 0.75. After initializing the problem, we tailored it using the following functions:

- `add_min_mesh_constraint()`, to ensure that the reforestation has the potential to restore the fragmentation level measured in 1976.
- `add_available_area_constraint()`, using a 150 m buffer around the existing track network (data freely distributed by the government of New Caledonia) to ensure that the selected reforestation areas are accessible, as the region is mountainous and difficult to access.

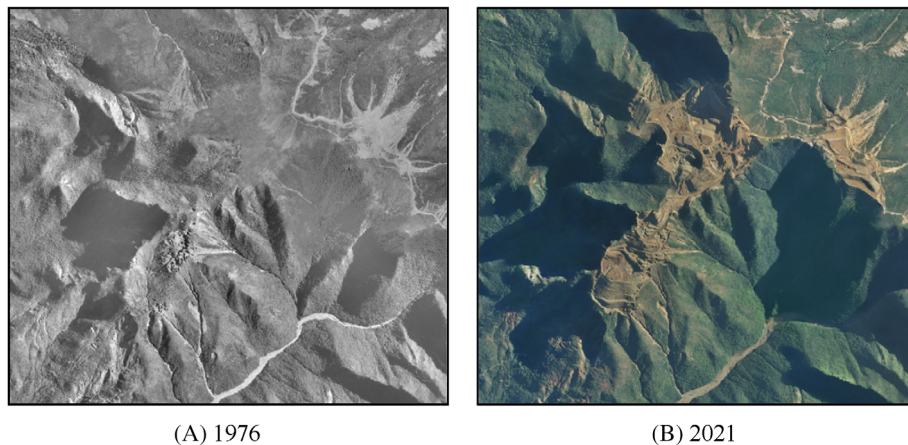


Figure 2. Aerial images located in the Mount Kaala mining area, between 1976 and 2021.

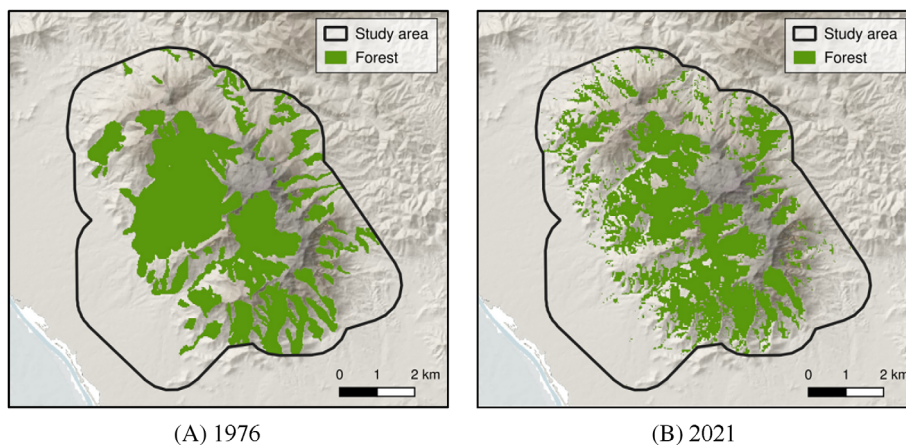


Figure 3. Digitized forest areas in the Mount Kaala (New Caledonia), from aerial images between 1976 and 2021, at 30 m × 30 m resolution. The study area includes all mining concessions in the Mount Kaala, surrounded by a 1,000 m buffer zone.

- `add_connected_constraint()`, to ensure that the reforestation area is spatially contiguous, which will ensure economies of scale.
- `add_compactness_constraint()`, to ensure that the spatial extent of the reforestation area is as compact as possible, to reduce implementation costs and improve accessibility. To determine an appropriate maximum diameter for this constraint, we first tried to solve the constraint satisfaction problem (i.e. with no optimization objective) with a 500 m diameter, but the solver found that it is impossible to satisfy the other constraints with this value. Thus, we gradually increased it until the solver could find several candidate solutions, which resulted in a maximum diameter of 920 m.
- `set_min_restore_objective()`, to identify solutions that satisfy the previous constraints at minimal cost (measured here in surface units to restore).

Given this problem formulation, we identified an optimal reforestation plan, which is depicted in Figure 4. Looking at the characteristics of this restoration plan (see Table 2), we can notice that a strategic restoration plan can restore the fragmentation level of 1976 with a relatively small cost (36 ha), compared to the forest cover loss that occurred between 1976 and 2021

Table 2. Forest cover and fragmentation level in 1976, 2021, and potential outcomes following an optimal restoration plan. Fragmentation is measured with the effective mesh size MESH (Jaeger 2000). Δ AREA and Δ MESH, respectively, represent the area and fragmentation evolution between the current period and the previous one.

Period	Forest Area (ha)	Δ AREA (ha)	MESH (ha)	Δ MESH (ha)
1976	1,984		202.4	
2021	1,819	-165	171.4	-31
Optimal restoration plan	1,855	+36	202.6	+31.2

(165 ha). A typical question that may arise is whether alternative restoration plans of similar quality exist. It is possible to answer this question by configuring the solver to output several solutions and by setting an optimality gap. Using the same constraints as previously and an optimality gap of 10%, we identified 1,000 near-optimal solutions, and we computed the selection frequency of each planning unit (see Fig. 5). What emerges from this analysis is that, under the current constraints, all near-optimal solutions occur in the same area, which indicates a strong potential of this particular area for curbing fragmentation at minimal cost in the Mount Kaala area.

Regarding the actual mining activity in the Mount Kaala area, this solution is conflicting with current exploitation plans, at least in a short-term vision. However, as these data are not

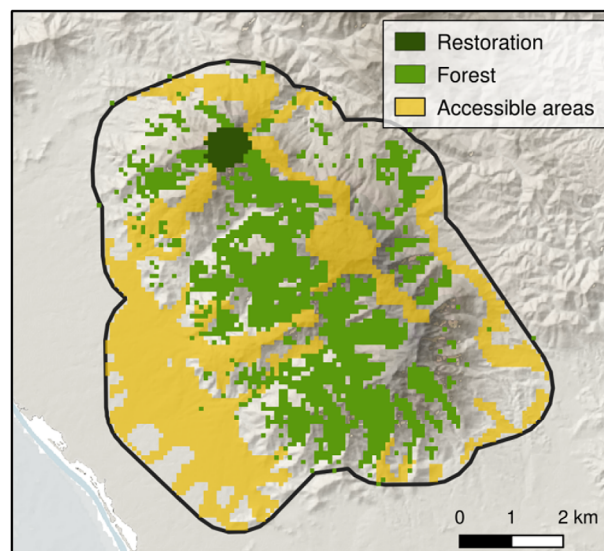


Figure 4. Reforestation plan in the Mount Kaala, minimizing the restoration cost and restoring the fragmentation level observed in 1976.

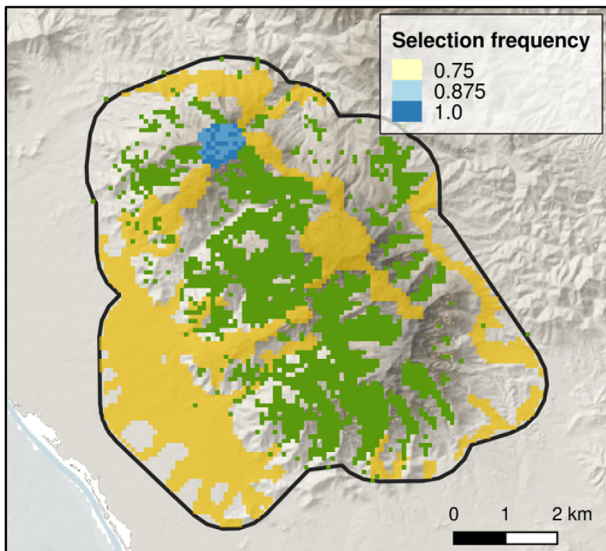


Figure 5. Selection frequency of planning units among 1,000 near-optimal reforestation plans.

available for reasons of confidentiality, we could not include them in the case study at this stage of the decision-support process. Consequently, this result should motivate further studies in coordination with stakeholders to include opportunity costs, mining phasing, and other vegetation types, such as shrubland (locally called “maquis minier”), which also hosts several threatened species (Lannuzel et al. 2021).

Discussion

The *restoptr* R package is a free and open-source decision support tool that takes advantage of CP to provide a generic framework for ecological restoration planning. It complements the existing conservation planning tools and opens perspectives include ecological restoration in land-use planning. Designed for ease of use and flexibility, *restoptr* is extensively documented and provides a broad catalogue of constraints and optimization objectives that can be composed to formulate a wide range of ecological restoration planning problems. This catalogue includes advanced landscape indices for optimizing ecological connectivity, and constraints to explicitly account for socio-economic factors.

In the case study, we demonstrated how *restoptr* can be used with historical data to set relevant targets over landscape indices. Specifically, relying on the forest cover comparison between 1976 and 2021, we identified a critical area that could restore the fragmentation level observed in 1976 at minimal cost for stakeholders. Besides, we also believe that a valuable outcome of this case study was the discussion that emerged after presenting the results to the stakeholders. Indeed, these discussions brought to light new information, such as the fact that the area we identified conflicts with current exploitations plans. Such situations are crucial in a holistic decision support context, as they allow refining our understanding of the issues,

and therefore of their solutions, iteratively. In addition, these situations can help highlight potentially missing data, identify sites for future fieldwork, and finally bring different stakeholders together around a medium that speaks to everyone: a map. As such, *restoptr* is a valuable tool for ecological restoration stakeholders because it provides high levels of expressiveness and flexibility in problem formulation and its performances in problem-solving are very well suited for iterative changes during the planning process.

Like conservation planning, ecological restoration planning encompasses various ecosystems and issues, and the application context often involves different specificities. Consequently, optimization objectives and targets can be tedious to formulate and vary a lot among application contexts. To address this challenge, we designed *restoptr* to be extensible and make the implementation of new features possible. For example, landscape patterns can be measured with various metrics, restoration costs can be heterogeneous across a landscape (Naidoo et al. 2006), and restoration can include different actions according to habitat type and quality. Accordingly, our perspectives include the integration of additional landscape metrics, heterogeneous restoration costs, and multiple types of restoration actions. In addition, we advocate that offering guarantees on solutions quality, which *restoptr* does thanks to CP, is a strength for such decision support processes. Indeed, not only do such guarantees allow for the accurate identification of the best possible trade-offs, but they also allow the identification of inconsistencies in targets.

In conclusion, decision support tools can help strategically address global targets in the current UN decade on ecosystem restoration. For example, the Bonn Challenge calls for 350 million hectares to be restored by 2030, and the Global Deal for Nature specifically calls for restoration actions to create corridors to connect protected areas (Dinerstein et al. 2019; Saint-Laurent et al. 2020). We developed the *restoptr* R package to provide a flexible, easily accessible, and transparent decision support tool for ecological restoration planning. We believe that it can be an asset to reach the global restoration targets by supporting cost-efficient and ecologically relevant restoration programmes.

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project.org/package=restopt) and its source code is available on GitHub (<https://github.com/dimitri-justeau/restopt/>) and on Zenodo (Justeau-Allaire & Hanson 2022). The *restopt* Java library source code is available on GitHub (<https://github.com/dimitri-justeau/restopt>) and on Zenodo (Justeau-Allaire & Prud'homme 2022). The source code of the case study is available in Supplement S1 and as a vignette in the package documentation.

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Supporting Information

The following information may be found in the online version of this article:

Supplement S1. Case study: using historical data to set ecological restoration targets.