INTRODUCTION TO CONSERVATION BIOLOGY AND SYSTEMATIC CONSERVATION PLANNING

Adapted from Justeau-Allaire, 2020

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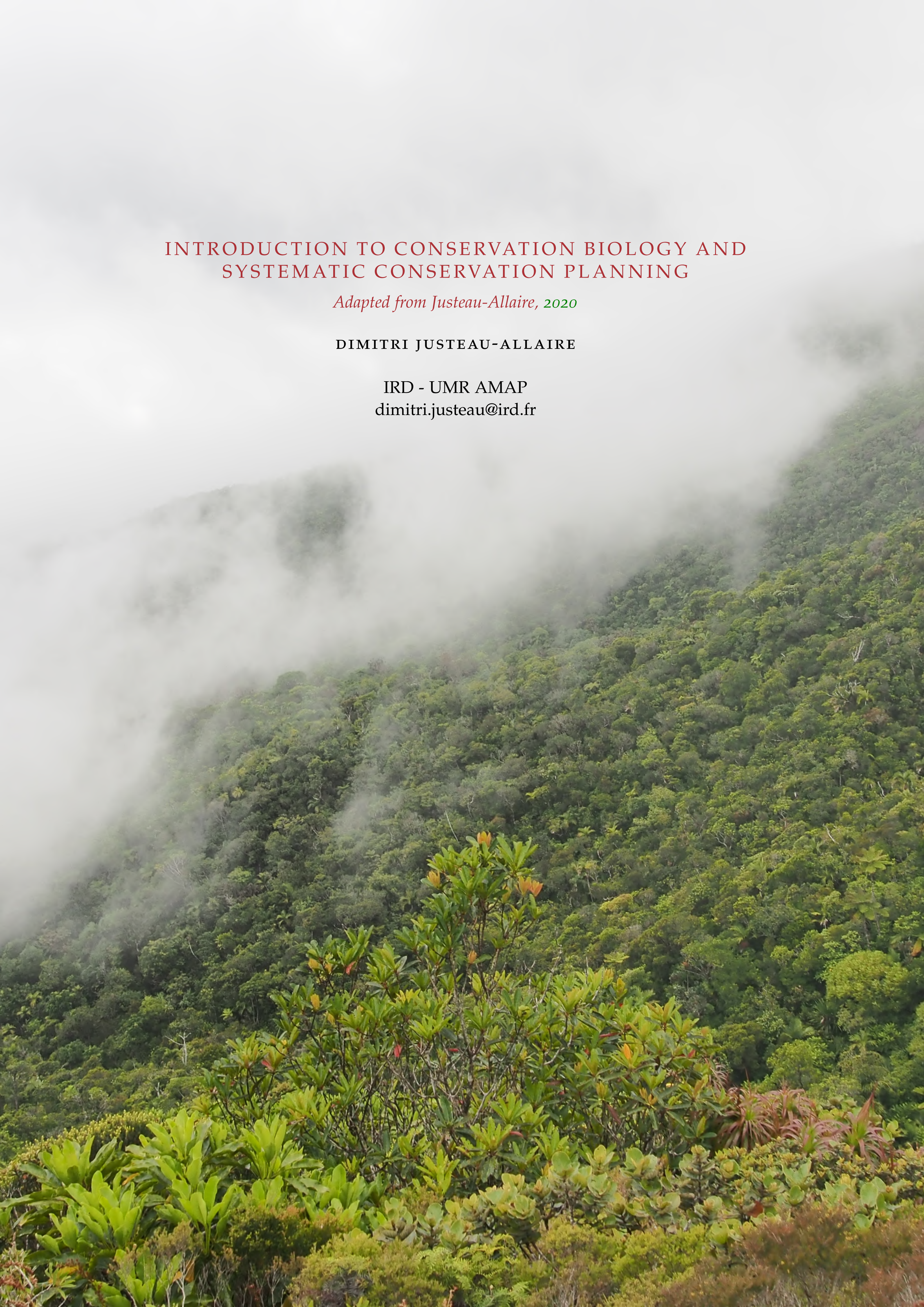


1

INTRODUCTION TO CONSERVATION BIOLOGY

In this first chapter, we introduce the interdisciplinary research field of Conservation Biology. We provide the historical context which led to its creation, its aims, and objectives. Finally, we discuss some successes and futures challenges for Conservation Biology.

1.1 The global nature crisis

The world is facing an unprecedented nature's crisis in human history, as ecosystems are declining along with biodiversity. Although accurate numbers are difficult to obtain, current species extinction rates are estimated 1000 times higher than the natural background rates, and about one million species are today threatened with extinction (Vos et al., 2015; Díaz et al., 2020). Anthropic activities are the principal cause of this crisis, which is known as the Holocene extinction (also referred to as the sixth mass extinction, or Anthropocene extinction). Land-use change is the most impacting of these activities, which includes agricultural expansion, urbanization, and natural resources exploitations such as mining or overfishing. Climate change, pollution, and invasive alien species are also major drivers of biodiversity and ecosystems decline. Many of these impacts on nature are already irreplaceable.

Though, in addition to its irrefutable intrinsic values, nature's provides resources and services that are vital to humans (Batavia and Nelson, 2017; Díaz et al., 2018). For instance, forests and woodlands are believed to host about 50% of the world's species, they produce just under half of the global terrestrial annual net primary production (amount of biomass produced per unit area and time, less plant respiration costs), and store about 50% of the world's terrestrial carbon stocks in their soils (Field et al., 1998; Groombridge and Jenkins, 2002). Moreover, forests provide many services. They protect watersheds, supply clean water, preserve soils from erosion, mitigate climate change, reduce air pollution, and provide many essential resources such as food, wood, or medicines. Despite, deforestation is one of the main consequences of land-use change. Between 1990 and 2015, the global forest area declined by 129 million ha. This loss mainly occurred in tropical forests, which are the richest and the most productive (Keenan et al., 2015).

As individuals of the species which has been causing so much damage to nature, we can feel concerned and willing to participate in the momentum of a society built around more respectful and sustainable models. This horizon is the leitmotif of nature conservation, which have led to the emergence of a dedicated science: conservation biology.

1.2 Origins, aim, and objectives of conservation biology

In the broadest sense, conservation defines as the preservation of something undamaged over time, or as the prevention of wasteful use of a resource. Nature conservation embraces both definitions, with two ethical motivations that are not mutually exclusive. In the first case, nature conservation is motivated by its perceived intrinsic value. In the second case, it is driven by the wish to provide sustainable access to the resources that nature offers to humans (from this point, conservation implicitly refers to nature conservation). It is possible to find conservation practices far back in the history of human societies. For instance, in medieval Europe, forests were named so from the low Latin word *foresta* which designates a prohibited land. Indeed, many forests were private areas whose enjoyment were reserved to nobles, for hunting, fishing and logging. Although based on a privilege now highly questionable, this practice can be seen as a conservation effort to preserve the resources provided by forests. In our recent history, the modern conservation movement was impulsed by naturalists in the mid-19th century. The first conservation organization, the Association for Protection of Sea Birds, was founded in England in 1868. A few years later, the first national park, Yellowstone, was created in the United States. It was the first example of a landscape-scale conservation effort, which is now at the core of most conservation policies through nature reserves.

Science always played an essential role in modern conservation. It has, however, only recently become a science itself, which emerged in 1978 with the First International Conference on Conservation Biology organized at the University of California by the biologist Michael E. Soulé. This meeting led to the publication of a foundational book, *Conservation Biology: An Evolutionary-Ecological Perspective* (Soulé and Wilcox, 1980). Five years later, the Society for Conservation Biology was the first scientific organization of this new discipline, which is now a well-established field, yet still burgeoning with many advances and innovative approaches[1]. The aim of conservation biology is to provide ethical and scientific responses to face the global nature crisis, protect species, preserve biodiversity and ecosystems. In this respect, it relies on three main objectives:

- Describing and understanding the diversity of species, communities, and ecosystems.
- Studying and quantifying the impacts of human activities on species, communities, and ecosystems.
- Developing practical, interdisciplinary, and integrated approaches to prevent species extinction, maintain genetic diversity among communities, preserve and restore biodiversity and ecosystems.

The first two objectives fall within the scope of fundamental research through a quest for knowledge and understanding. The third objective, on the other hand, also defines conservation biology as action and standard-setting science. In this regard, conservation biology is an applied scientific discipline based on the ethical values of nature conservation. Another specificity of this research field is its highly interdisciplinary nature (cf. Figure 1.1). If environmental and ecological sciences were at the core of conservation biology, it also relies on human and social sciences where some fields emerged along with the modern nature conservation movement. For example, environmental philosophy, which developed in the 1970s, is concerned by humans' relationship with their natural environment and by morals values that stem from it. More recently, mathematical and information sciences have been increasingly involved in conservation biology. Taking the example of computer science, bioinformatics established about fifty years ago but is mostly associated with

1 For a more detailed history of conservation biology, interested readers can refer to the first chapter of *Conservation Biology: Foundations, Concepts, Applications* (Van Dyke, 2008).

genomics. Biodiversity informatics gained prominence at the beginning of the 21st century (Bisby, 2000) with a focus on taxonomic and biodiversity data and a broader scope of applications. In the same line, ecoinformatics appeared with an emphasis on ecological rather than taxonomical applications (Kareiva, 2001; Dengler et al., 2011). Lately, another term emerged from computer science communities: computational sustainability (Gomes, 2008). There is little doubt that these fields are overlapping. There is even less doubt that we are witnessing a major shift in conservation biology through the growing use of mathematical and information sciences.

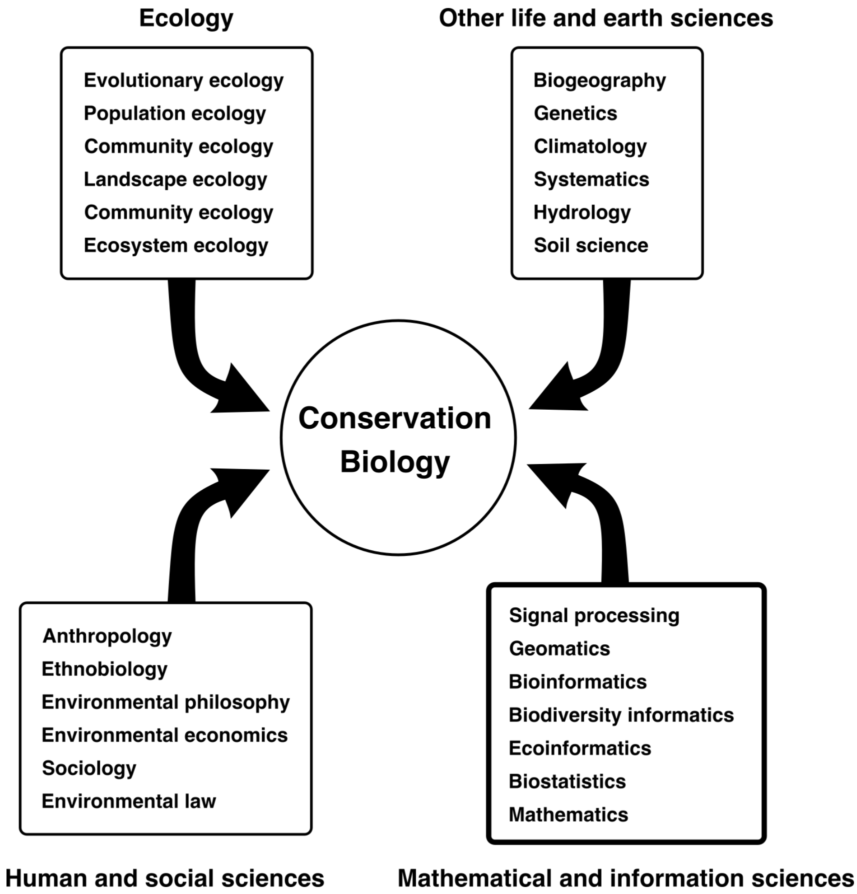


Figure 1.1: Scientific disciplines contributing to the interdisciplinary field of conservation biology. Adapted from Temple, 1991, with the addition of mathematical and information sciences fields.

Following the third objective of conservation biology, the union of these many disciplines aims to synthesize knowledge into new techniques and principles to improve the management of nature. Such transfers from research to implementation may involve identifying priority areas to protect, defining environmental legislative frameworks, developing new economic models, or supporting sustainable land-use planning (cf. Figure 1.2).

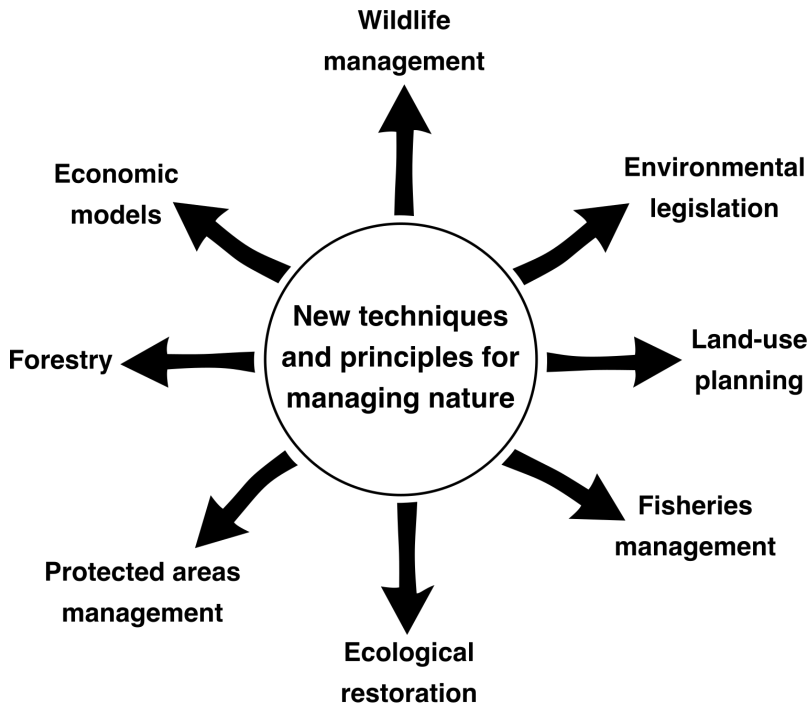


Figure 1.2: Transfers for conservation biology to nature management. Adapted from Temple, 1991.

1.3 SUCCESSES AND CHALLENGES OF CONSERVATION BIOLOGY

With more than forty years of existence, conservation biology established as a recognized and successful science from an academic perspective. Many universities teach conservation biology, and the number of publications has been steadily growing since the creation of the discipline. For instance, the number of papers submitted to the journal *Conservation Biology* from 1993 to 2006 has increased by 13.2% on average (Meffe, 2006). The field has also been successful in getting closer to the non-academic world: conservation biology has involved in the United Nations, national and regional agencies, non-governmental organizations (NGOs), citizen groups, etc.

But, is conservation biology achieving its goal? This question has intricate answers. What stands clear is that the global nature crisis has not been halted, as the latest Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) report indisputably shows, as have many other studies (Cardinale et al., 2012; Haddad et al., 2015; Keenan et al., 2015; Woinarski et al., 2015; Strona et al., 2018; Díaz et al., 2020). However, conservation biology significantly influenced the principles and practices of conservation and has several success stories to relate. One significant example is the International Union for Nature Conservation (IUCN) red list of threatened species (see Figure 1.3). Established by the IUCN (an international conservation NGO), it is now a recognized international standard which is influencing policies, resource allocation, and conservation planning. Assessments from conservation scientists contribute to this list, as well as the list guides conservation research (IUCN, 2020). More success stories are described in Boxes 1.1, 1.2, and 1.3.

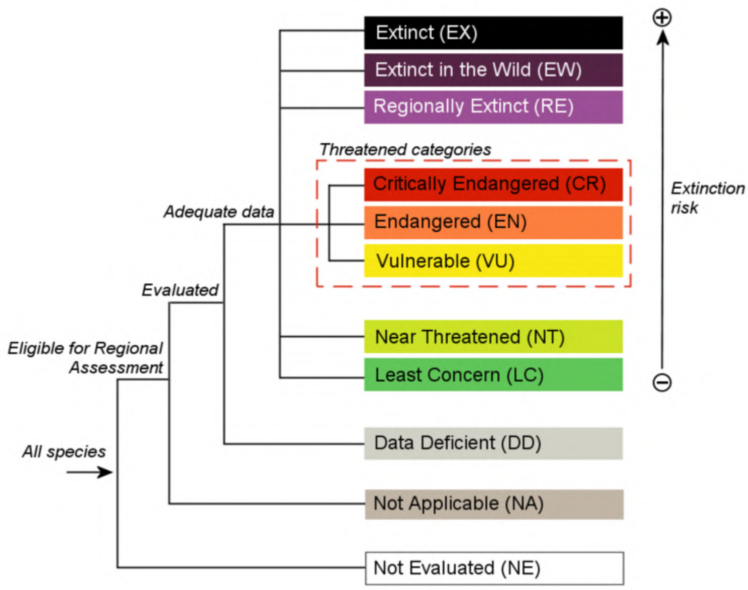


Figure 1.3: Categories of the International Union for Nature Conservation (IUCN) red list of threatened species. ©IUCN

Yet, despite substantial growth, numerous achievements, and clear recognition, conservation remains a weak social machine when compared to industries, finance, or armies. Powerful political and commercial organizations whose interests are conflicting with those of conservation constitute an obstacle, along with the consumerist way of life in many societies (Buckley, 2015). As a scientific field, conservation biology cannot solve the problem alone, but should nonetheless be involved in advocacy, following its third objective (see Section 1.2). In this sense, many conservation scientists depicted the *research-implementation gap* over the past few years (Robinson, 2006; Knight et al., 2008; Game et al., 2015; Wistbacka et al., 2018; Williams et al., 2020). Indeed, despite a burgeoning literature on conservation assessments and techniques for performing such assessments, research results are rarely translated into actions. Several trails could help to bridge this gap, such as engaging a closer dialogue between scientists and managers (Prendergast et al., 1999), working more closely with political and social sciences (Balmford and Cowling, 2006), directly involving as scientists in implementation (Arlettaz et al., 2010), or even getting more politically involved (Ellison, 2016).

In the following part, we focus on one particular aspect of conservation biology, conservation planning, which aims to provide decision support for land-use planning, wildlife and protected areas management, or even ecological restoration. Conservation planning directly falls within the third main objective of conservation biology (see Section 1.2) by adopting as a strategy an involvement in decision-making processes that are related to conservation. Through better decisions, conservation planning can offer solutions to reduce the negative impacts of land-use change and improve the effectiveness of conservation actions. Over its history, conservation planning have been increasingly relying on modelling and computer science, attracting more and more scientists from these fields. This modern and systematic approach of conservation planning is now referred as systematic conservation planning.

Box 1.1: Recovery of the Seychelles warbler after translocation.

The Seychelles warbler (*Acrocephalus sechellensis*) is a small passerine endemic to the granitic islands of Seychelles. Destruction of its habitat and introduction of invasive predators made it one of the rarest birds in the world in the mid 20th century, with a population of 26 individuals. Previously occurring in several islands, it only remained in the Cousin Island (Crook, 1965). Intensive conservation action started in 1968 with the purchase of the Cousin island by a consortium led by BirdLife International (at this time called the Internation Committee for Bird Protection). Habitat management led the population to recover and to remain stable, and the species was translocated to four other islands between 1988 and 2011 (Wright et al., 2014). The population of the Seychelles warbler now comprises more than 3000 mature individuals and is increasing. Its conservation status has changed from Threatened to Near Threatened between 1988 and today (IUCN, 2016).

Figure 1.4: The Seychelles warbler (*Acrocephalus sechellensis*). ©Remi Jouan, CC BY-SA 3.0.

Box 1.2: Ban of deep-sea trawling in European Union.

Deep-sea trawling is a fishing technique developed at the end of the 20th century as a response to the collapse of surface-water resources. It consists of dragging a fishing net along the seafloor. This method is not selective and extremely harmful to deep-sea slow-growing species and ecosystems. Many conservation scientists warned on the dangers of this practice (Gage et al., 2005; Pusceddu et al., 2014; Victorero et al., 2018). Their scientific results provided the basis for intensive advocacy campaigns, led by NGOs (such as Bloom and the Deep Sea Conservation Coalition) and citizen groups. In June 2016, the European Union finally banned deep-sea trawling below 800 meters in its waters.

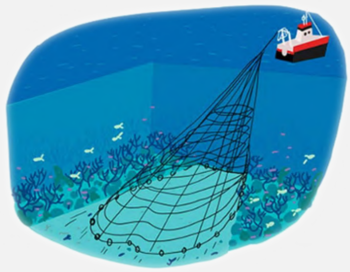


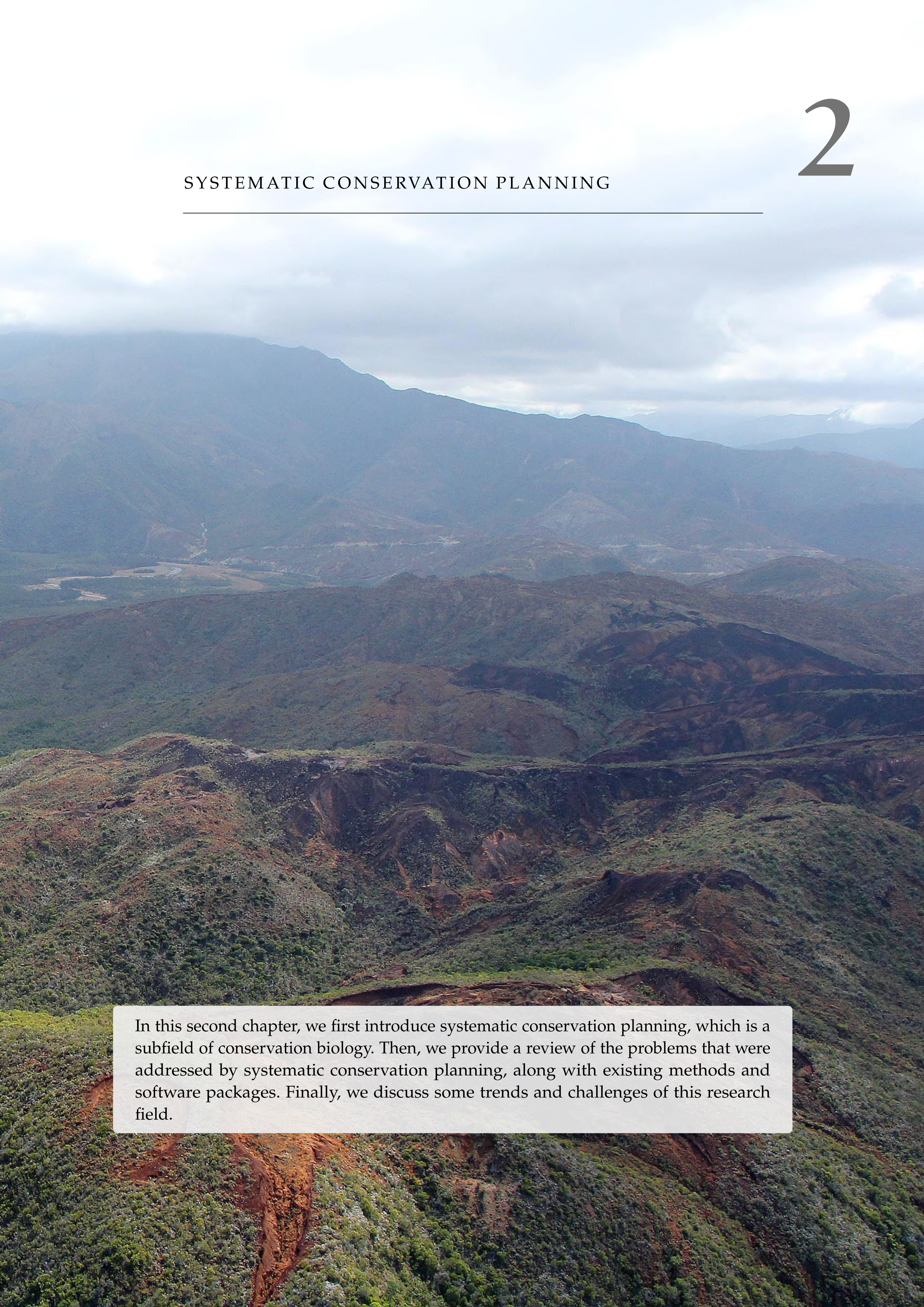
Figure 1.5: Illustration of deep-sea trawling ©Pénélope Bagieu.

Box 1.3: Protection of Tasmanian endemic and endangered plant species with the first reserve selection algorithm.

Tasmania is an Australian island located 240 km to the south of the mainland, which hosts a unique flora and fauna. For example, among 1530 native vascular plant species, 20% are endemic. However, logging and fire have been threatening several of these species. In 1983, the researcher Jamie Kirkpatrick developed and applied an iterative method to identify a set of areas that should be protected to preserve 25 endemic and endangered plant species. By the late 1990s, each of the seven new reserves recommended by Kirkpatrick was protected and preserved from logging. His method is now considered as the first reserve selection algorithm for conservation planning (Kirkpatrick, 1983; Pressey, 2002).

Figure 1.6: Douglas-Apsley National Park in Tasmania, extended in 1989 after Kirkpatrick's recommendations. ©VirtualWolf, CC BY-SA 2.0.

2 SYSTEMATIC CONSERVATION PLANNING



In this second chapter, we first introduce systematic conservation planning, which is a subfield of conservation biology. Then, we provide a review of the problems that were addressed by systematic conservation planning, along with existing methods and software packages. Finally, we discuss some trends and challenges of this research field.

Landscape-scale conservation through reserves is a foundational and well-established practice in nature management. However, reserves have long been developed in an opportune manner and motivated by the protection of scenic, recreational, or inspirational places of little economic interest. By the end of the 20th century, conservation scientists started advocating a more systematic selection and delineation of reserves, with the primary motivation of effectively sustaining biological diversity (Myers, 1988; Pressey et al., 1993). In 2000, this concern came to be known as a sub-discipline of conservation biology called *systematic conservation planning* (SCP) (Margules and Pressey, 2000), which now encompasses other issues such as ecological corridor design or restoration planning, or conservation projects prioritization.

First concerns for SCP emerged from island biogeography theory: viewing nature reserves as islands surrounded by an ocean of altered habitat, a set of geometric principles (see Figure 2.1) were devised to produce efficient reserve delineations (MacArthur and Wilson, 1967; Diamond, 1975). However, those principles quickly became controversial, notably because areas surrounding reserves are not as inhospitable as the ocean is for terrestrial organisms and because they assume ecosystems to be at equilibrium state, which is very unlikely to be satisfied in anthropized and fragmented landscapes (Margules et al., 1982). Moreover, according to the context, it may be safer to establish several distant reserves to preserve the whole from natural catastrophes, forest fires, or diseases. Similarly, in heterogeneous landscapes, a single large reserve cannot guarantee the preservation of a large proportion of species (Higgs, 1981).

During the 1980s, many researchers tried to put emphasis on biodiversity features representation rather than geometrical properties of reserves. The first approaches consisted in multi-criteria scoring procedures (e.g. Margules and Usher, 1981; Smith and Theberge, 1986; Usher, 1986; Smith and Theberge, 1987). Nonetheless, several authors quickly showed that such methods are inefficient in their goal because they rely on a local reasoning which cannot spot the complementarity between sites in the representation of biodiversity features (Kirkpatrick, 1983; Pressey and Nicholls, 1989). Rather, they found that much better results can be achieved using iterative procedures, which were called reserve selection algorithms (see Box 1.3). Soon after, complementarity was recognized as key principle of reserve selection (Vane-Wright et al., 1991; Pressey et al., 1993) and many methods have been devised in this direction (e.g. Rebelo and Siegfried, 1992; Possingham et al., 1993; Underhill, 1994; Ball, 2000).

It is now widely recognized that, instead of geometric principles, we should regard spatial attributes contextually along with biodiversity features representation. Since its introduction, SCP has now well established, with many methodological and applied papers. The field has even attracted researchers from the mathematical optimization and computer science areas. Indeed, one interesting thing about SCP is that it involves constraint satisfaction and optimization problems that are theoretically and computationally challenging. As an example, identifying the minimum requirements to represent a complete set of endangered species in a reserve network, namely ensuring complementarity, equates the *set cover problem* in combinatorics, computer science, and operations research (Underhill, 1994; Camm et al., 1996). This problem lies in the NP-Complete computational complexity class. In simplified terms, solving this problem is challenging (see Boxes 2.1 and 2.2 for a more detailed explanation). Usually, SCP involves a combination of such hard problems and therefore addresses original and novel questions to modelling and computer science.

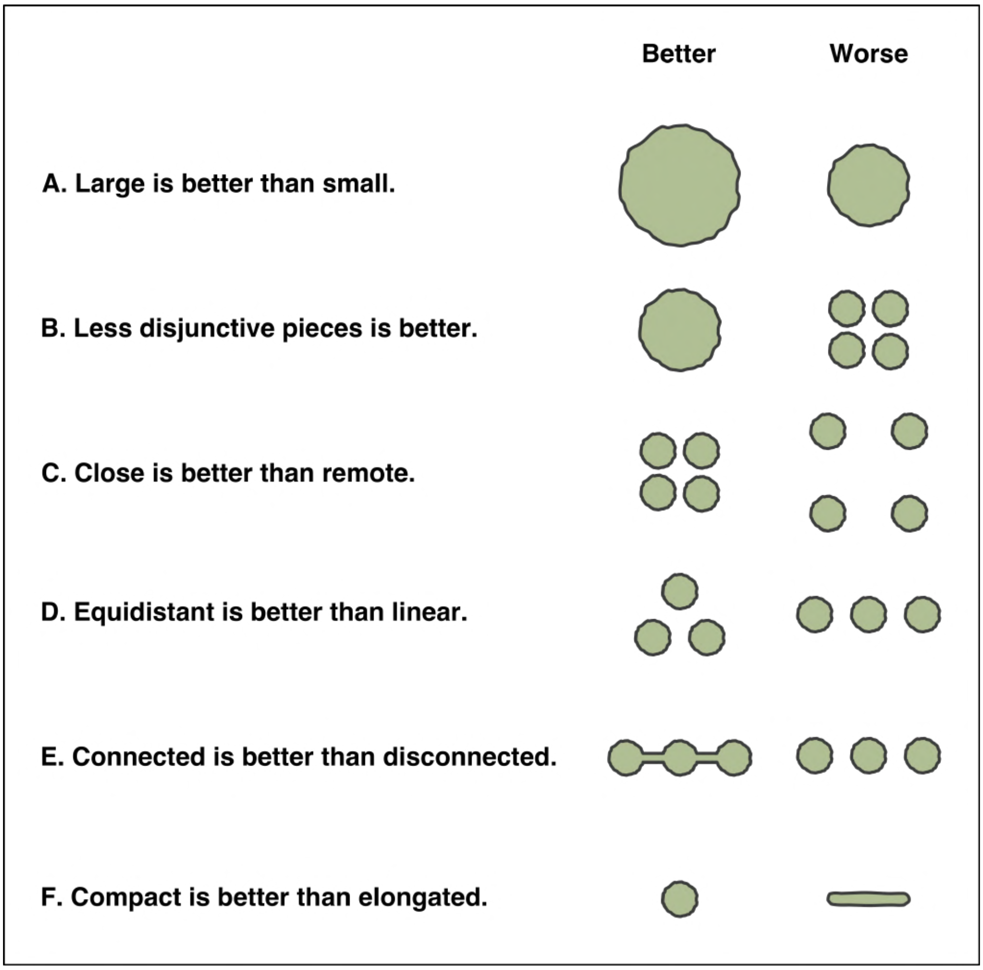


Figure 2.1: Diamond's geometric principles for reserve design, inspired from island biogeography theory. Adapted from Diamond, 1975.

Box 2.1: Computational problem.

In theoretical computer science, computational problems are those that analytical methods cannot solve, and for which we need algorithms. We distinguish four main types of such problems, all illustrated with the undirected graph G (also called network) represented in Figure 2.2:

- A *decision problem* is such that, given an input, the solution is either yes or no. For example: "Is there a path from a to f in the graph G ?". The answer is yes.
- A *search problem* is such that, given an input, a solution is an object satisfying the problem's statement. For example: "Find a path from a to f in the graph G". A solution is: a $\rightarrow$ c $\rightarrow$ d $\rightarrow$ f.
- An *optimization problem* is similar to a search problem, at the difference that the expected solution must be optimal according to one or more criteria. For example: "Find a shortest path from a to f in the graph G" (the length of a path being the number of links). A solution is a $\rightarrow$ b $\rightarrow$ f.
- A *counting problem* refers to a search or optimization problem for which is expected the number of solutions. For example: "Count the shortest paths from a to f in the graph G". The solution is 2.

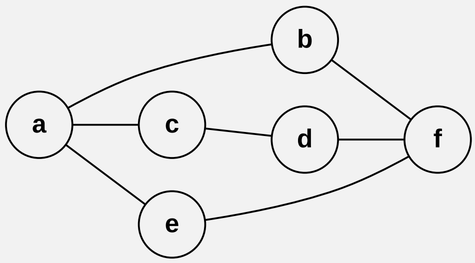


Figure 2.2: Undirected graph G.

Box 2.2: Computational complexity.

In theoretical computer science, computational complexity focuses on studying and classifying computational problems according to their intrinsic difficulty. It also investigates the relationships between classes. Computational complexity classes inform on the resources (time or memory) needed by an algorithm to solve a given problem. For example, the class **P** contains all decision problems that can be solved with a deterministic algorithm in polynomial time (i.e. number of operations needed) according to the input. The class **NP** contains all decision problems that can be solved with a non-deterministic algorithm in polynomial time. A problem is said **NP-hard** if any problem in **NP** can be reduced to it in polynomial time, and if such a problem belongs itself to **NP** it is also said **NP-Complete**. **NP-hard** problems are challenging because a non-deterministic computer is a theoretical construct with no physical implementation. We thus cannot solve **NP-hard** problems in polynomial time with deterministic computers (unless P=NP), such problems can quickly become intractable in practice. Computational complexity theory is a broad and complex research area, interested readers can refer to Arora and Barak, 2009 or Perifel, 2014.

Researchers devised many computational methods to solve SCP problems. These methods have, of course, much in common, but they also differ a lot in the techniques used and on the types of question they can address. In this section, we try to establish a concise state of the art, focusing on spatially-explicit methods, which are prevalent in this field (Margules and Pressey, 2000). We will complete it in chapter 4 with a comprehensive nomenclature of SCP problems. First, we provide a very generic formalism that is suitable for any spatially-explicit SCP problem: given a geographical space $\mathcal{S}$, delineate n regions $R_0, ..., R_{n-1}$ within $\mathcal{S}$ such that conservation goals are met. In the vast majority of cases, $\mathcal{S}$ is discretized into sites (e.g. regular square grid). For instance, if we need to delineate a reserve protecting a set of endangered species in a study area, we will try to delineate a single region such that each species occurs in it. Many criteria can be used to express conservation goals, they can be classified in two main categories: feature representation and spatial criteria.

2.2.1 *Feature representation criteria*

A feature designates a characteristic of the geographical space $\mathcal{S}$ that can be spatially represented with numerical values. Most of the time, biodiversity features (e.g. occurrences) are used to ensure properties such as complementarity. However, socio-economic values (e.g. exploitable land, customary area) can also be represented as features to express managers' constraints and quantify the trade-offs between different solutions. Features can be described with three data types: binary data (e.g. species occurrence), quantitative data (e.g. species abundance, land acquisition cost), and probabilistic data (e.g. species distribution models). Let $\mathcal{F}$ be a set of features and R_i a region, the feature representation criteria that have been used in the literature so far are the following:

Occurrence representation. The representation in R_i of at least one occurrence for each feature in $\mathcal{F}$, that is ensuring that R_i is a cover of $\mathcal{F}$. This criteria can also be used for optimization, by maximizing the number of occurring features from $\mathcal{F}$ in R_i for example. This criteria can be used when binary or quantitative data is available, and corresponds to the principle of complementarity (e.g. Vane-Wright et al., 1991; Church et al., 1996; ReVelle et al., 2002). See Figure 2.3 for an illustration.

Abundance representation. The representation in R_i of a minimum abundance for each feature in $\mathcal{F}$, when quantitative data is available (e.g. Margules et al., 1988; McDonnell et al., 2002; Watts et al., 2009). This criteria can also be used for optimization, by maximizing the abundance of a given feature for example.

Occurrence representation with backups. The representation in R_i of an occurrence for each feature in $\mathcal{F}$, in at least k distinct sites, when binary or quantitative data is available (e.g. Margules et al., 1988; ReVelle et al., 2002; Delmelle et al., 2017). This criteria can also be used for optimization, by maximizing k for example. See Figure 2.3 for an illustration.

Probabilistic representation. The representation in R_i of a minimum probability of presence for each feature in $\mathcal{F}$, when probabilistic data is available (e.g. Haight et al., 2000; ReVelle et al., 2002; Billionnet, 2011). This criteria can also be used for optimization, by maximizing the minimum probability of presence of features from $\mathcal{F}$ in R_i for example.

Phylogenetic diversity (PD). Some authors also considered the representation of a minimum phylogenetic diversity (PD) among the features represented in R_i (e.g. Moulton et al., 2007; Billionnet, 2017). This criteria can also be used for optimization, by maximizing PD. This criteria applies when $\mathcal{F}$ corresponds to binary or quantitative data of taxonomic entities, PD is thus computed from a phylogenetic tree where each entity in $\mathcal{F}$ must be represented.

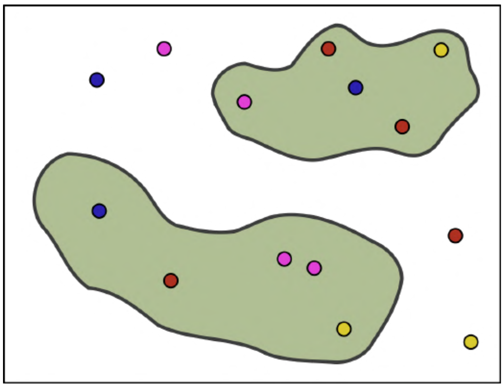


Figure 2.3: A reserve system ensuring complementarity (occurrence representation) for all species of interest, as well as occurrence representation with backups (each species is represented in at least two distinct sites). Each colour represents a species.

2.2.2 *Spatial criteria*

Spatial criteria are useful to control the spatial configuration of solutions. They can involve biological concerns such as the satisfaction of minimum requirements to ensure species persistence, but also management concerns such as ensuring that a reserve is accessible from an existing track network. Such criteria can involve a single region, or several regions that must relate to each other in a certain way (e.g. be adjacent).

Connectivity. Ensuring the connectivity of a region R_i is a frequent concern. Most of the time, connectivity is characterized through a graph, which can represent the adjacency between sites but also species dispersal capabilities (e.g. Sessions, 1992; Briers, 2002; Wang and Önal, 2011; Billionnet, 2016; Jafari et al., 2017). See Figure 2.4 for an illustration.

Number of connected components. Instead of ensuring full connectivity, the need for controlling the number of connected components of a region R_i was formalized by Williams et al. (2005). Hof and Flather (1996) devised a model allowing the control of the number of component, but only when regions are circular or rectangular, and Williams (2002) proposed a model allowing a maximum number of disconnections. For example, the reserve system represented in Figure 2.3 has two connected components.

Perimeter of a region. The perimeter (or boundary length) of a region R_i can also be considered. It can be used as a surrogate to approximate connectivity, or even be minimized to ensure the compactness of a reserve (e.g. McDonnell et al., 2002; Ball et al., 2009; Weerasena et al., 2014).

Size of a region. The size of a region R_i was spotted as an important spatial attribute which can be constrained, maximized or minimized (e.g. ReVelle et al., 2002; Williams et al., 2005). This criteria can, however, also be considered as a feature representation one, especially when the sites have different areas.

Size of connected components. Similarly, when a region R_i is not connected, it may be desirable to control the area of its connected components, to ensure populations persistence in a reserve network for example. This criteria has only been addressed when the candidate connected components are delineated a priori (Rothley, 1999; Williams et al., 2005).

Distance between regions. The distance between two regions R_i and R_j, or between the connected components of a region R_i, can be useful to control for facilitating species migration between reserves, or preserving a reserve from negative edge effects of a urbanized area for example (e.g. Rothley, 1999; Williams, 2008; Önal et al., 2016).

Buffer zone. Another frequent requirement is the design of a buffer zone R_b between a protected core area R_i and a non-protected area R_j. Such a buffer zone is useful to preserve a reserve from negative edge effects, or to nest several levels of protection (e.g. Williams and ReVelle, 1996; Billionnet, 2013; Cheng et al., 2015). See Figure 2.4 for an illustration.

Shape of a region. The shape of a region R_i can be important for ensuring species persistence or for management. Most of the time, we need a region to be compact, which can be ensured through its perimeter/area ratio, or by ensuring a maximum distance between every pair of sites within the region (e.g. Williams et al., 2005; Billionnet, 2016).

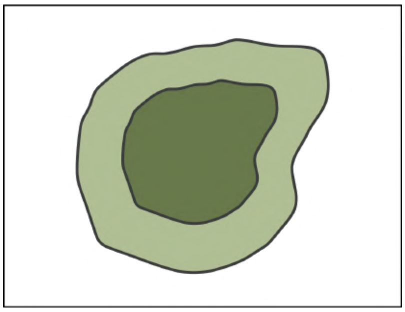


Figure 2.4: Example of a connected protected core area surrounded by a protected buffer zone.

2.2.3 *Techniques*

Different techniques can address and solve SCP problems. As the questions can widely vary in their structure, criteria, or application context, and because the underlying computational problems pose challenges, we cannot claim that one technique is dominating the others (to the exception of scoring techniques that have many limitations, as explained in Section 2.1). Instead, each has its strengths, weaknesses, and performs adequately for a specific class of problems.Most of current SCP solving approaches mostly rely on ad hoc heuristics, metaheuristics, and mixed-integer linear programming (Sarkar et al., 2006). Novel approaches are also emerging from constraint programming (Justeau-Allaire et al., 2021) and reinforcement learning (Silvestro et al., 2022). In the following, we briefly describe these techniques. We also inform on their genericity, flexibility, and guarantees regarding runtime, satisfiability and optimality. The *genericity* of a technique refers to the extent to which it can be used to address different problems. Its *flexibility* refers to the ease with which it can be adapted to new types of problems. A technique offers *runtime guarantees* when it provides control over the time needed to produce a solution. It provides *satisfiability guarantees* when it can ensure whether the solutions satisfy the constraints. It offers *optimality guarantees* when it yields control over the quality of solutions (according to an optimization objective and relative to the optimal solution). Finally, it offers *robustness to changes* when it is able to take advantage of dynamics to take into account the impact of solutions in the future. These characteristics are summarized in Table 2.1.

Ad hoc heuristics. Problem-specific local search algorithms, they employ practical methods to quickly find solutions to a pre-formulated problem. Ad hoc heuristic are either based on a constructive (greedy) algorithm (e.g. Kirkpatrick, 1983; Rebelo and Siegfried, 1992; Nicholls and Margules, 1993), or destructive (stingy) algorithm (e.g. Zonation software; Moilanen et al., 2009a) Such algorithms are fast and can be adapted to prioritization problems, but lack genericity and cannot always provide guarantees such as constraint satisfaction and optimality, which is the necessary price for bypassing the combinatorial complexity. For overly large and complex problems, intractable by exact approaches, ad hoc heuristics are useful to find good solutions.

Metaheuristics. High-level and problem-independent optimization algorithms. They offer the same characteristics as ad hoc heuristic, with a higher level of genericity and flexibility, but still no systematic guarantees on constraint satisfaction and optimality. Popular metaheuristics include tabu search, genetic algorithms, ant colony optimization algorithms, or simulated annealing which is used in SCP by Marxan software (Ball et al., 2009), or in McDonnell et al. (2002).

Mixed-integer linear programming (MILP). Mathematical optimization approach where the objective function and the constraints are stated as linear inequalities, with some or all the variables are integers. With less guarantees on the runtime for complex and large problems, MILP provides constraint satisfaction and optimality guarantees. Another advantage of MILP lies in its declarative nature, it offers a modelling language to represent a problem as well as a generic solving method, which confers it a high level of expressiveness, genericity, and flexibility (e.g. Rodrigues et al., 2000; Billionnet, 2013; Dilkina et al., 2017; oppr R package, Hanson et al., 2019).

Constraint Programming (CP). High-level declarative approach for modelling and solving constraint satisfaction and constrained optimization problems. In this context, declarative means that the modelling of a problem is decoupled from its solving process, which allows the primary focus to be on what must be solved rather than describing how to solve it. CP is a subfield of artificial intelligence which relies on automated reasoning, constraint propagation and search heuristics. As an exact approach, CP can provide constraint satisfaction and optimality guarantees, as well as enumerating every solution of a problem. The main difference between CP and MILP is that CP supports non-linear constraints, and various types of variables (e.g. boolean, integer, set, graph) (Rossi et al., 2006; Justeau-Allaire et al., 2021).

Reinforcement learning (RL). Machine learning approach which is based on the notion of reward. In RL, an autonomous agent learns how to take the best decisions through the maximization of this reward, which thus defines what is a *good* decision. In conservation planning, RL was recently used in a policy-search context. The reward is a defined such that is minimized the biodiversity loss, according to the predicted impact (through simulations) of conservation actions (Silvestro et al., 2022). In this context, RL is an innovative approach because it integrates well the notion of dynamics and changes over time. However, it currently addresses a specific class of problems and lacks the integration of constraints, notably spatial ones.

Table 2.1: Characteristics (genericity, flexibility, and guarantees) of the five main techniques currently used in systematic conservation planning: ad hoc heuristics, metaheuristics, mixed-integer linear programming (MILP), constraint programming (CP), and reinforcement learning (RL).

	Genericity	Flexibility	Guarantees
Ad hoc heuristics	Low	Low	Runtime
Metaheuristics	High	Middle	Runtime
MILP	High	High	Satisfiability, Optimality
CP	High	High	Satisfiability, Optimality
RL	Middle	Middle	Robustness to changes

2.2.4 *Software packages*

An important factor for dissemination and use of SCP approaches is their availability. In this respect, software packages are very useful, but only some approaches have been released in this form. We compiled a (non-exhaustive) list of currently available state-of-the art SCP software packages, and summarized it in Table 2.2.

Marxan (Ball et al., 2009). Marxan is a target-based SCP software based on simulated annealing, a metaheuristic optimization technique inspired from the annealing process in metallurgy (interested readers can refer to van Laarhoven and Aarts, 1987). Marxan addresses a problem which can be formulated as following: given a tessellated geographical space $\mathcal{S} = [0, n[$, a cost c_i for each site i, a set of features $\mathcal{F} = [0, k[$, a representation amount a_{ij} for each site i and each feature j, a target t_j for each feature j, and a connectivity cost cv_{i_1,i_2} for each pair of site $\{i_1, i_2\}$ (most of the time the connectivity cost corresponds to the boundary length), find a region $R \subseteq \mathcal{S}$ (most of the time a reserve network) minimizing the following objective function:

$$\sum_{i\ \in R} c_i + b \sum_{i_1 \in R} \sum_{i_2 \in \mathcal{S} \setminus R} cv_{i_1,i_2} + \sum_{j \in \mathcal{F}} FPF_j FR_j H(s) \left(\frac{s}{t_j} \right). \qquad (2.1)$$

The first term corresponds to the total cost of the region R, as Marxan tries to achieve user targets at minimum cost. The second term corresponds to the weighted connectivity cost (e.g. boundary length) of R, where b is a penalty factor used to control the relative importance of connectivity in the objective function. The third term corresponds to the penalties for violating feature representation targets, FPF_j is a feature penalty factor for the feature j, and FR_j the cost for satisfying the target for feature j only. The term s corresponds to the amount of representation unsatisfied for the feature j, such that $s = t_j - \sum_{i \in R} a_{ij}$. $H(s)$ is a step function such that $H(s) = 0$ if $s \leqslant 0$ and $H(s) = 1$ otherwise. Because it relies on simulated annealing, Marxan needs to integrate the constraints in the objective function. Thus, their satisfaction cannot always be guaranteed, and the results are sensitive to penalty factors' values.

Marxan is distributed as a free software and offers a graphical user interface (GUI). Marxan with zones is an extension which allows the user to delineate several regions at the same time, with distinct targets (e.g. several levels of protection) (Watts et al., 2009). Zonae Cogito is a software which enables a direct interaction with Marxan and databases through a geographical information system (GIS) interface. More recently, Marxan Connect was released as an alternative GUI to facilitate the incorporation of connectivity issues in Marxan (Daigle et al., 2020).

Zonation (Moilanen et al., 2009b). Zonation is prioritization SCP software relying on an ad hoc local search heuristic. At the difference of most SCP approaches, Zonation does not rely on a target-based paradigm (although there is an option to use it for target-based planning, see Moilanen, 2007). Instead, it ranks every site from a tessellated geographical space $\mathcal{S} = [\![0, n[\![$ from the most to the least valuable, according to a set of features $\mathcal{F} = [\![0, k[\![$ given as input data. The user can define a number of regions to delineate as hierarchical zonations, for instance: the 10%, included in the top 20%, included in the top 30%, etc. The prioritization algorithm starts from the full landscape, then iteratively removes sets of sites from the remaining area. At each stage of the algorithm, the set to remove is selected such that is minimizes a loss function, which can be chosen among a predefined catalogue. For example, the basic core-area Zonation loss function is defined as follows for each site i:

$$\sigma_i = \max_{j \in \mathcal{F}} \frac{q_{ij} w_j}{c_i} \tag{2.2}$$

Where w_j is a weight associated to the feature j, c_i the cost associated to the site i, and q_{ij} the proportion of the feature j in the site i according to the remaining sites. Using this loss function, the algorithm will remove at each stage the site where the feature with the highest weighted proportion divided by the site cost is minimal. Besides, an aggregation method can be selected among a predefined catalogue to guide the heuristic towards less fragmented solutions (e.g. boundary length penalty). Such aggregation methods directly alter the loss function to include connectivity consideration. Zonation is distributed as a free software and offers a GUI.

C-Plan (Pressey et al., 2005; Pressey et al., 2009). C-Plan was designed as an integrated and interactive decision support system for SCP that can be used during negotiations between stakeholders. It links with GIS (ESRI ArcView 3) and relies on a statistical estimator to compute irreplaceability of sites and ensure complementarity (Ferrier et al., 2000). C-Plan can also be linked with Marxan. We did not find much more details on C-Plan's underlying mathematical model, but it seems to distinguish mainly by its emphasis on irreplaceability, interactivity, feature representation criteria, without spatial criteria. The project is apparently discontinued, as we could not find any active download link.

ConsNet (Ciarleglio et al., 2009, 2010). ConsNet is a target-based SCP software based on a metaheuristic optimization technique called tabu search (Glover, 1989, 1990; Ciarleglio, 2008). Given a tessellated geographical space and a set of features, ConsNet aims at delineating a region (most of the time a reserve network) either satisfying targets on feature representation at minimum cost or maximizing feature representation under cost constraints. The first problem is the same as Marxan's, but ConsNet offers more spatial criteria in both formulations:

- Compactness, through the perimeter/area ratio measure.
- Connectivity, through minimization of the number of connected components.
- Replication, which is the number of connected components criteria extended with feature representation with backups requirements.
- Alignment, which aims to coincide the delineated region with existing units (e.g. ecoregions, watersheds). As matter of fact, this criteria can also be considered as a feature representation criteria: the delineated region must cover a minimum area of existing units.

ConsNet also provides an interactive multi-criteria analysis to explore possible trade-offs between equivalent solutions, is distributed as a free software, and offers a GUI.

Conefor (Saura and Torné, 2009). Conefor cannot be exactly considered as a SCP software, it can however be useful for conservation planning. The aim of this software is to quantify the level of connectivity over a landscape through graph-based indices. A graph (also called network) is a mathematical object composed of vertices (or nodes) and arcs (also called edges or links) between the vertices, see Figure 2.2 for an example). Therefore, the user must provide a graph representation of a landscape, or a reserve network for example. Conefor Sensinode can compute several indices and quantify the importance of nodes. That is, how would a given index vary if a given node is added or removed from the network. Conefor is provided as a free software, with a GUI available only for Windows, and a command-line interface available for Windows, Mac, and Linux.

Prioritizr R package (Hanson et al., 2020). Prioritizr is an R package that was designed to solve a wide range of SCP problems with MILP. Prioritizr can solve similar problems as Marxan and Zonation, and also allows the user to delineate several regions, just as Marxan with Zones. Prioritizr integrates feature representation criteria in the form of constraints (e.g. occurrence representation) or optimization objectives. For example, Prioritizr allows the maximization of phylogenetic diversity under budget restrictions. The package also integrates spatial criteria, that can apply as penalties in the objective function (as Marxan does) or as hard constraints. Currently, Prioritizr allows control over the perimeter of regions (boundary length) as penalty in the objective function, over connectivity of regions as penalty or hard constraint, and over the minimum number of neighbours of selected sites as hard constraint. Because Prioritizr relies on MILP, it can provide optimality and satisfiability guarantees to the problems it formulates.

LQGraph (Fuller and Sarkar, 2006). LQGraph is a software package specifically designed to delineate corridors between existing protected areas. From quality scores (e.g. habitat suitability) defined for each site outside protected areas, LQGraph designs optimal corridors that can inform managers on the extension of protected areas. LQGraph can also be used to identify sites that can efficiently isolate protected areas to prevent the spread of pathogens or invasive species.

Linkage Mapper (McRae et al., 2012). Similarly to LQGraph, Linkage Mapper is specifically designed to identify optimal corridors between habitat patches. It relies on a raster-based resistance model where each raster cell is characterized by a value which represents the ability of focal species to migrate through. From such a model, Linkage Mapper computes minimal resistance corridors between habitat patches.

Restoptr R package (Justeau-Allaire et al., 2021). Restoptr is an R package specifically designed for ecological restoration planning. It relies on CP, and implement various constraints and optimization objectives, including state-of-the-art fragmentation and connectivity indices from landscape ecology. This variety of constraints and objective can be composed to express and solve a wide range of restoration planning problems. Because restoptr relies on CP, it can provide both optimality and satisfiability guarantees.

Captain (Silvestro et al., 2022). Captain is a conservation prioritization software based on RL. It distinguishes from previous approaches by taking into account temporal trends in its prioritization process. Specifically, under a budget constraint, Captain aims at identifying a set of priority planning units for conservation such that it minimizes the biodiversity loss over time, according to simulations. Captain is distributed as free and open source Python package.

Table 2.2: Summary of currently available state-of-the-art systematic conservation planning software packages (non-exhaustive list). MILP: Mixed-Integer Linear Programming, GUI: Graphical User Interface, CLI: Command-Line Interface, GIS: Geographic Information System.

	Technique	Interface	Short description
Marxan (Ball et al., 2009)	Simulated annealing	GUI/CLI	Target-based conservation planning with boundary length penalty.
Zonation (Moilanen et al., 2009b)	Backward heuristic	GUI/CLI	Hierarchical prioritization for land-use planning.
C-Plan (Pressey et al., 2005)	Heuristic	GIS (ArcView)	Interactive decision support for conservation planning.
ConsNet (Ciarleglio et al., 2009)	Tabu search	GUI/CLI	Target-based conservation planning with several spatial spatial criteria.
Conefor Sensinode (Saura and Torné, 2009)	Graph-based	GUI/CLI	Quantification of inter-patch connectivity through graph-based indices.
Prioritizr (Hanson et al., 2020)	MILP	R package	Exact MILP target-based conservation planning in R.
LQGraph (Fuller and Sarkar, 2006)	Graph-based	GUI	Design of optimal corridors between existing protected areas.
Linkage Mapper (McRae et al., 2012)	Least-cost models	GIS (ArcGIS)	Optimal corridors between habitat patches based on a least-cost resistance model.
Restoptr (Justeau-Allaire et al., 2021)	CP	R package	Ecological restoration planning with advanced landscape indices.
Captain (Silvestro et al., 2022)	RL	Python package	Robust conservation prioritization.

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