Introduction

Biodiversity, a contraction of the words biological and diversity, represents the diversity of living organisms (animals, plants, fungi, and bacteria) and their living environments (aquatic, terrestrial, underground, aerial). The diversity of living organisms refers to the diversity of species and the diversity of genes within each species. The species richness of a given place, *i.e.*, the number of species present in that place, is a widely used measure to quantify the biodiversity of that place. This measure is easy to interpret, but inventorying the species present at a given location can be a difficult and costly exercise. Some species such as higher plants and vertebrates are easy to observe but this is not the case, for example, with fungi and bacteria. The number of individuals of each species is also an interesting indicator. It can also be difficult to estimate. Genetic diversity essentially corresponds to the diversity of alleles – versions of a gene – within individuals of the same species. This diversity, which results from mutations and reproduction between individuals, allows species to adapt to changes in their environment. Observing this diversity requires sophisticated and relatively expensive techniques. The notion of biodiversity also includes the interactions that exist between living organisms and also the interactions between these organisms and their living environments. Today's biodiversity is the result of a slow evolution of the living world, spread over billions of years and affecting the entire planet. There is a broad consensus that the preservation of biodiversity is currently a major issue. Biodiversity provides irreplaceable and essential goods for our survival, such as food, oxygen, medicines, and raw materials. In addition, species such as insects, bats, and birds pollinate plants. Finally, natural environments contribute to natural water purification, flood prevention, landscape structuring, and the quality of our living environment.

There is also a broad consensus to consider that biodiversity loss is accelerating and that the five major causes of biodiversity loss are habitat destruction (*e.g.*, urbanization, deforestation, wetland drying), biological invasions (*e.g.*, Japanese knotweed, coypu), pollution (*e.g.*, release of a large number of toxic substances into

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the environment and wide distribution of these substances), overexploitation of species (*e.g.*, African and Asian rhinos, bluefin tuna, ebony) and climate change, including its rate. For example, according to the World Wildlife Fund (WWF), global vertebrate populations declined by almost 70% between 1970 and 2016. Stopping the loss of biodiversity is, therefore, one of the major challenges facing the international community today. Many countries are committed to take early action to halt biodiversity loss.

Protected areas play a decisive role in maintaining biodiversity because they make it possible to directly target the protection of elements at high risk of extinction. Thus, at the 10th Conference of the Parties in Nagoya (COP 10), the signatory countries adopted a Strategic Plan for the period 2011–2020 with 20 key objectives to improve biodiversity conservation. Target 11 sets the global coverage of protected areas to be at least 17% of terrestrial and inland water areas and at least 10% of marine areas. These protected areas may require the restoration of degraded habitats such as reforestation, reintroduction of species, control of invasive species, and restoration of wetlands. They can be created on a regional, national or even international scale and be linked in networks in a physical or organizational way. They already occupy a significant fraction of the Earth's surface and generally aim to preserve several aspects of biodiversity simultaneously. They can also protect species still unknown to scientists. Some species are very sensitive to human presence and many activities can be prohibited within protected areas, such as habitat transformation, hunting, fishing, tourism, and sports. The term protected area is now very often used. However, there are many other terms used to designate these regulated areas for nature protection: nature park, nature reserve, protected zone, conservation area, protected site, etc. The International Union for Conservation of Nature (IUCN) identifies six categories of protected areas, terrestrial and marine, according to their management objectives and defines a protected area as "a clearly defined, recognized, dedicated and managed geographical area, by any effective legal or other means, to ensure the long-term conservation of nature and its associated ecosystem services and cultural values". Ideally, each threatened species or, more broadly, each threatened ecosystem should benefit from an area whose protection ensures its future. In some regions, protected areas may be the only remaining natural areas. As a result, they can support species that are not found elsewhere. To simplify the presentations we will mainly focus in this book on the protection of species, but all the developments could be applied to the protection of other aspects of biodiversity.

Several indicators can be used to measure the effects generated by the creation of protected areas, such as the number of protected species, their degree of vulnerability, the population size of each protected species, the genetic or phylogenetic diversity of protected species, or combinations of these indicators. This measure of the effects of protection may also include the ecosystem services it provides, such as food, water, cultural values, health products, and recreational areas. However, these aspects can be difficult to assess. The protection of natural areas is also an effective strategy for mitigating climate change. Protected areas must be large enough and suitable for the protection of the targeted protection, but at the same time must not be too detrimental to the needs and habitats of the populations living in or near these areas. Given these human pressures and the direct costs associated with protected areas, a trade-off will often have to be made between the ideal size of protected areas and the size ultimately chosen. The delimitation of protected areas often helps to avoid excessive habitat fragmentation. Non-contiguous protected areas can be organized in a network for global management. They can also be more or less linked by biophysical connections such as biological corridors. Finally, an assessment of the effects of protection must be carried out regularly to ensure that it is effective, *i.e.*, that the objectives of maintaining biodiversity are being met. Indeed, the objective of some protected areas may not be achieved due, for example, to illegal behaviour or climate change. Good management of these areas is, therefore, extremely important. There are other species' protection strategies such as, for example, the control of invasive species or captive breeding followed by reintroduction into the wild. The latter strategy may be necessary in an emergency situation. Of course, the development of protected areas, although extremely effective in conserving biodiversity, is not, on its own, sufficient to ensure such conservation. Thus, using land-use and biodiversity models, researchers have recently shown that an approach combining important land protection measures and a transformation of the food system would make it possible to redress the curve of biodiversity loss by 2050.

We are interested here in the choice of natural sites to be protected with the main objective of protecting biodiversity – representation and persistence – but this biodiversity protection can be combined with other objectives (*e.g.*, preservation of drinking water, cultural heritage, and creation of a recreational, research or educational area, flood prevention). As the resources available for this protection are obviously limited, it is important to use them as effectively as possible. It is recognized that protected areas have saved important species and natural environments. However, the erosion of global biodiversity continues at a rapid rate. This is why the creation of new protected areas as well as the optimal choice of them is important. The objectives, many and varied, must be well defined, the possible actions must be identified and the impact of these actions must be assessed. For example, a good knowledge of the geographical distribution of endangered animal and plant species is fundamental. A large number of studies on the selection of sites whose protection is relevant to biodiversity conservation have been published in the operational research and biological conservation literature.

In this book, we provide an overview of classical but also original problems related to the "optimal" design of a network of protected areas, focusing on the modelling approach and finally on their resolution. By "design of a network of protected areas" we mean the process of choosing, within a territory, portions of territories to be protected, *i.e.*, managed with the explicit aim of contributing to the protection of certain species and ecosystems associated with these territories. These territories and portions of territories can be very different in size. Many problems are considered and described in detail in this book – some of them have already been the subject of occasional publications on my part – but this overview is far from exhaustive, as there are so many questions inherent in the optimal design of a protected area network. Numerous references are presented. They concern both the field of optimisation in general and the field of protected area design.

We show how to approach these optimisation problems in a unified framework, that of mathematical programming. Within this framework, we propose efficient and often innovative modellings. Mathematical programming (linear, quadratic, fractional, and convex, in real or integer variables, by objectives) is a branch of mathematics that focuses on finding the "best" solution to a problem, among a very large number of possible solutions. It generally consists in studying and solving a problem expressed as the search for the optimum of a function of n variables. This function – called objective function or economic function – enables the quality of a solution to be measured in relation to the pursued objectives, the variables being subject to linear or non-linear constraints expressed by equalities and inequalities. The objectives may be technical, ecological, sociological, economic or a combination of them. Mathematical programming is, therefore, a very general framework for addressing optimization problems that arise in many fields. Research in this domain of mathematics has been stimulated for many years by the possibility of using more and more powerful solvers such as, for example, IBM-ILOG-CPLEX, FICO-XPRESS or GUROBI. Their impressive performance is based on theoretical and algorithmic results, the effective implementation of these results and the spectacular increase in computer computing speed. It is thus currently possible to solve mathematical programs with thousands of variables and constraints and even much more in the case of linear programming. One of the important advantages of mathematical programming – compared to other approaches for dealing with optimization problems – is its flexibility. It is very easy to modify the objective function and constraints, if this is necessary to take into account, for example, variations in the objectives or characteristics that the desired protected areas must satisfy. In this book, we study many optimization problems associated with the design of a protected area network and show how to formulate them in the framework of mathematical programming. We will see that all kinds of complex objectives and constraints can be easily taken into account. The considerable interest of this approach lies in the fact that, when a problem is formulated in this way, the computer implementation of its resolution is particularly simple using a modelling language coupled with a solver, and powerful languages of this type as well as extremely efficient solvers – mentioned above – are available. The efficient computer implementation of an algorithm specially designed for a particular problem is generally much more difficult. The mathematical programming approach is, therefore, particularly appropriate to help a decision-maker to quickly consider a project to design a network of protected areas. We have just mentioned the technical advantages of mathematical programming to address the problems associated with the design of protected zones. Another advantage of this approach is that in order to be tackled in this way, the problems must be analysed rigorously, since the objectives, constraints and data must be precisely defined. This will often provide an opportunity to clarify certain points. Finally, and this last aspect is extremely important, the solutions proposed are impartial and transparent. However, the fact that a problem can be formulated as a mathematical program does not imply that it can be solved in a reasonable time. Furthermore, the decision-makers and protected area managers must be closely involved in the construction of the models. Note that graph theory is also widely used in this book, mainly as a modelling tool used prior to a mathematical programming formulation. Graph theory is a rich branch of discrete mathematics that studies networks of points connected by lines called arcs or edges.

Many publications in the biological conservation literature address these optimization problems related to the delimitation of protected areas, but they often propose to deal with them by approximate methods, specific heuristics or metaheuristics. These latter are generic heuristics that must be adapted to each problem. These approximate methods are relatively easy to implement and may require less computation time than that required to solve a mathematical program, but they can provide solutions whose value is quite far from the value of the optimal solution. Moreover, it is not generally known whether the value of the solution provided is close or not to the value of the optimal solution. More recently, some problems related to the creation of protected areas that are "optimal" in terms of biodiversity protection have been addressed within the framework of constraint programming.

An important aspect to be taken into account in the design of a network of protected areas is the uncertainty regarding the effects of these nature protection policies. Indeed, a large number of uncertainties exist in the medium and long term about the factors influencing biodiversity. Some are due to human activities such as agriculture, urbanization or climate change, at least in part, others are simply due to errors in measurements and forecasts. There are many approaches to try to account for this uncertainty. It can be conventionally translated into probabilities – difficult to define. These probabilities concern specific events affecting biodiversity and likely to occur in the future given the protection policies adopted. For example, it can be estimated that the probability that a certain species will have disappeared from a certain site in 10 years is 0.9 if no particular action is taken for the protection of this species in this site. This uncertainty can also be taken into account in other ways. For example, it can be assumed that several scenarios – coherent sets of assumptions – are possible and the forecasts used to construct the models will depend on the scenario. For example, it can be considered that the sites whose protection would allow the survival of a given species over a 50-year period are different depending on the scenario considered. Both scenarios and probabilities can also be taken into account simultaneously. For example, it can be considered that the survival probability of a species in a given area and over a certain time horizon depends on the scenario. Another way of taking uncertainty into account is simply to consider that the different values of measurements or forecasts, in the medium or long term, are subject to uncertainties or errors. For example, the population size of a given species in a given area may be estimated to be between 1,000 and 1,500 units after 10 years, or the survival probability of a given species in a given area over a 50-year period may be estimated to be between 0.8 and 0.9. Of course, this type of uncertainty can be combined with considering several scenarios.

Let us now present a little more precisely the general framework of this book. We consider a set of species, animal or plant, or other aspects of biodiversity, that are in risk of disappearing. To simplify the presentation throughout this book, reference will almost always be made to a set of threatened species, but all the proposed approaches would easily adapt to other threatened aspects of nature and biodiversity, such as valuable habitats or ecological processes. It should be noted that according to the World Wildlife Fund (WWF) many common species are also experiencing a significant decline that should at least be slowed down. A certain horizon (*e.g.*, 10 years, 50 years or 100 years) and a set of zones – also called sites or parcels or areas – where these species live are considered. These zones can be very different in nature (*e.g.*, natural zones of ecological, faunistic and floristic interest, zones of the Conservatoire du Littoral, rivers, wetlands). The protection of these different zones can have a very different but complementary impact on biodiversity protection. At the beginning of the horizon considered, it may be decided to protect certain zones in order to provide some protection to the species considered and present in these zones, and thus increase their chance of survival. These decisions may eventually be called into question throughout the horizon under consideration if this is still possible. Protection measures are appropriate to the conservation objectives sought and vary from one zone to another. Thus, certain activities may be authorized in one protected zone and strictly prohibited in another (*e.g.*, destruction of embankments or hedges, construction, hunting, fishing, certain agricultural activities, public circulation, gathering). One way to protect a zone is to include it in a nature reserve. Protecting a zone has a cost. This cost takes into account, for example, the acquisition of the zone and its management over time. It may also reflect some costs that are more complex to assess such as social costs. It is also considered, as mentioned above, that the decisions taken require consideration, as far as possible, of the various uncertainties. To protect a given species or a given set of species, different measures to protect the zones can be adopted. In general, the more important these measures are, the greater the chances of survival of the species concerned – their survival probabilities – are. Thus, with any subset of protected zones is associated an assessment of the value of protecting these zones. For example, it can be simply considered that there are only two possible decisions for a zone, to protect it or not during the period considered, and that its protection automatically ensures the survival – survival probability equal to 1 – of the species present in that zone at the beginning of the period. Thus, in this case and for figure I.1a, the protection of the zones z_2, z_5, z_{16}, and z_{18} ensures the survival of the species s_3, s_4, s_6, s_7, s_9, and s_{11}.

Let us now look at the survival probability of the species. First of all, let us consider the case where only one scenario is envisaged. By definition, the survival probability of a given species throughout the period considered depends on the protection measures decided in favour of that species at the beginning of the period. In one of the extreme cases, where this probability takes the value 0, the species certainly disappears and in the other extreme case, where this probability takes the value 1, it certainly survives. Let us again take the example of figure I.1a and assume that the survival probability of the species present in a zone at the beginning of the period considered is equal to 0 if the zone is not protected and 0.5 if the zone is protected. Let us also assume that the interest associated with the protection of zones is measured by the mathematical expectation of the number of species that will survive, in all zones, protected or not, until the end of the period. Thus, the protection of the zones z_2, z_4, and z_{11} provides an interest equal to 2.5 while the protection of the zones z_{10}, z_{19}, and z_{20} provides an interest only equal to 2.375. For these calculations, it is assumed that all the probabilities are independent. In a

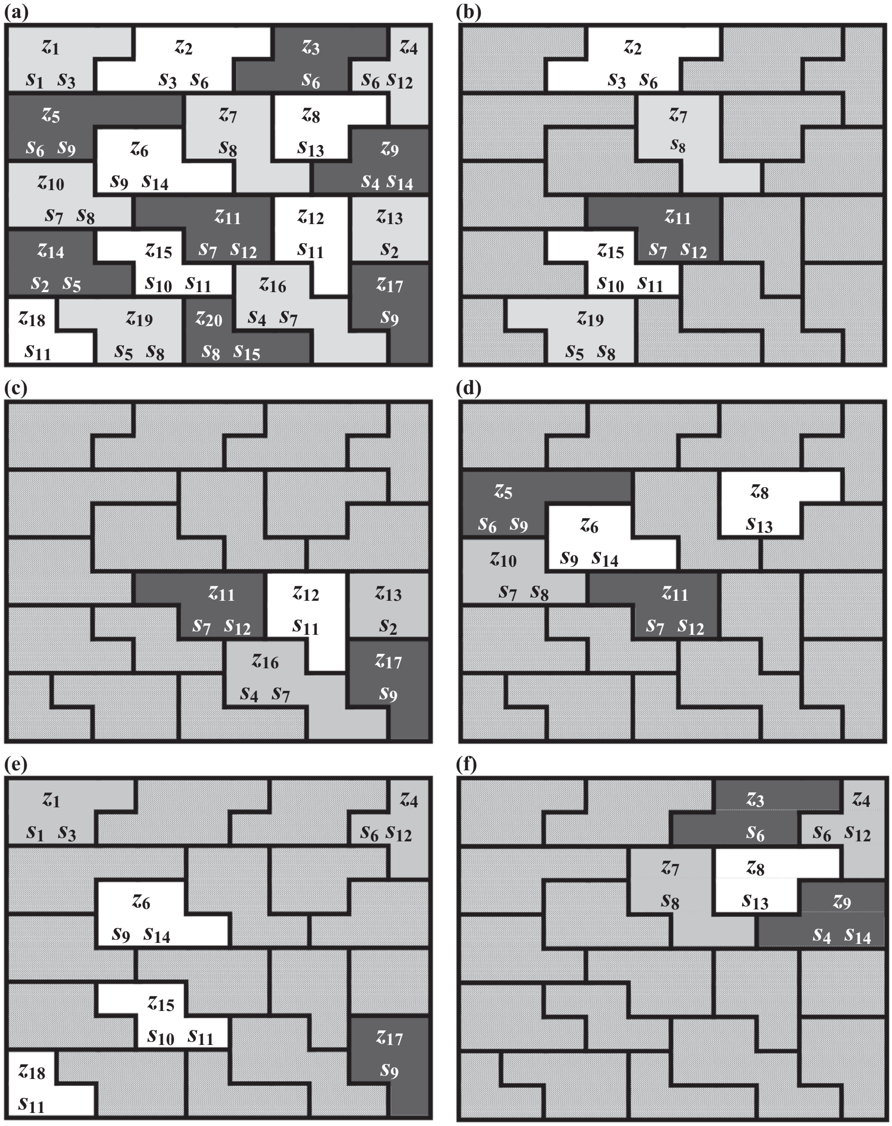

FIG. I.1 – (a) A hypothetical set of 20 candidate zones for protection and the list of species living in each of these zones, among the 15 species considered. The cost of protecting the white zones is equal to one unit, the cost of protecting the light grey zones is equal to two units and the cost of protecting the dark grey zones is equal to four units. (b) Protection of five zones forming a one-piece but not very compact reserve which protects, at least in some way, the 8 species s_3, s_5, s_6, s_7, s_8, s_{10}, s_{11}, and s_{12}. (c) Protection of five zones forming a single, compact reserve. (d) Protection of five zones forming two reserves in one piece and relatively close to each other. (e) Protection of six zones forming a highly fragmented reserve. (f) Five zones are protected but only z_8 belongs to the central part of the reserve, the other four zones share a common border with unprotected zones and thus form a buffer part of the reserve.

general way, these probabilities are obviously difficult to establish. One way of taking into account the uncertainty that inevitably affects these probabilities is to consider, for example, that they belong to a certain interval.

Consider now the case where several scenarios are possible. By definition, the survival probability of a given species throughout the period considered depends as before on the protection measures decided in favour of that species at the beginning of the period but also on the scenario that is envisaged. As in the case of a single scenario, this probability can take any value between 0 and 1, including the values 0 or 1, or it may not be known with certainty, in which case only the interval to which it belongs is known. Similarly to the case of a single scenario, with any subset of protected zones is associated an assessment of the interest provided by the protection of these zones – in terms of biodiversity protection – but, in the case of several scenarios, this interest depends on the scenario under consideration.

Below are some examples of constraints that may be imposed on a set of zones that are being considered for protection. For example, we can impose purely spatial constraints on this set of zones, which we call, for the sake of simplicity, "reserve". These constraints may concern the shape of the reserve, its connectivity, *i.e.*, the contiguity of the different zones composing it, its compactness and its degree of fragmentation measured by different indicators, its edge length, *i.e.*, the length of the transition zones between two different habitats, etc. It should be noted that biodiversity and habitat quality within these transitional areas, the edges, can be negatively affected (alterations at the microclimate level, interactions between species such as predation and competition, development of invasive species). Therefore, efforts will generally be made to limit the "edge effect" as much as possible. However, these areas are sometimes favourable to certain interesting species.

Let us return to the example in figure I.1. Figure I.1b shows a set of 5 protected zones, in one piece but relatively non-compact. On the contrary, figure I.1c shows a set of 5 protected zones, in one piece and compact. Figure I.1d shows a set of 5 zones, relatively compact but made up of two groups of zones of a one-piece each. Figure I.1e shows a highly fragmented reserve of 6 zones.

Once we are able to define the interest associated with the protection of any subset of zones, for any possible scenario, several problems naturally arise. A first type of problem is to determine the optimal set of zones to protect, given limited resources and constraints on the selected zones. In the case of a single scenario, an optimal set of zones is a set of zones of maximal interest. In the case of several scenarios, an optimal set of zones is more difficult to define. This could be, for example, a set of maximal interest in the worst-case scenario, *i.e.*, in the scenario that is the most unfavourable to the set of selected zones. We can also search for a set of zones whose interest, regardless of the scenario that occurs, is not too far from the interest of the set of maximal interest for that scenario. This allows for the identification of a feasible set of zones within the available budget and minimizing the maximal relative difference, the maximal "regret", over all the scenarios, between the interest provided by the protection of this set of zones for the scenario under consideration and the maximal interest that could have been achieved if it had been known that this scenario would occur. A second type of problem is to determine the feasible set of zones of minimal cost that must be protected to achieve a certain interest. In the case of a single scenario, this amounts to determining a set of zones, with a minimal cost and whose protection interest is greater than or equal to a certain value. In the case of several scenarios, an approach may be developed to identify a set of zones, with minimal cost and protection interest that is greater than or equal to a certain value for all the scenarios considered. This value may depend or not on the scenario.

We now give some examples of measures of the interest associated with the protection of a subset of zones – called a reserve for simplicity's sake – with regard to biodiversity. This interest can be assessed by the following measures, or a combination of them: the number or mathematical expectation of the number of species protected by the reserve; the diversity or mathematical expectation of the diversity of species protected by the reserve, measured in different ways (*e.g.*, phylogenetic diversity, Simpson diversity index); the size of the populations of the species protected by the reserve; the amount of carbon sequestered and/or captured by the reserve over time. If more than one scenario is considered, all these measures may be scenario-dependent.

Some examples are also given below of conditions that must be met with regard to the zones of the reserve in order to increase the biodiversity protection in this reserve and over the period considered: the reserve must contain, at the beginning of the period, a total number of species of a given set greater than or equal to a certain threshold value; the zones of the reserve must be sufficiently close to each other or even contiguous; the reserve must have a central part and a buffer part (for example, a zone can be considered to belong to the central part of the reserve if it is "completely surrounded" by other zones of the reserve, see figure I.1f); the reserve may have several contiguous "sub-reserves" but these must be linked by a network of biological corridors; in order to guard against natural risks that may occur and destroy certain zones of the reserve (*e.g.*, storm, fire, and flooding) species must be protected by several zones. Again, these conditions may depend on the scenario.

In everything we have just seen, protection strategies consist, for a given zone, in protecting it or not. The result is a set of protected zones and finally a more or less strong protection, possibly non-existent, of the species or ecosystems concerned. The relationship between "protected zone" and "chances of survival of a species" can be quite complex. A generalization of all this consists in considering that there are, for each zone, several levels of protection and not just one. For example, for a given zone, the survival probability in that zone of a given species is 0.5 if the zone is not protected, 0.8 if a certain level of protection is provided for that zone, and 0.9 if another – higher – level of protection is provided.

In summary, an important objective of this book is to help those who have to make decisions regarding the establishment of a network of protected areas to do so in an "optimal" way, *i.e.*, in the best possible way with regard to the protection of some biodiversity aspects while taking into account various constraints. Specifically, this means selecting the zones to be protected from a set of candidate zones and determining the level of protection to be applied to these zones. These decisions, aiming at the best possible protection of biodiversity, must take into account the criteria chosen to assess biodiversity, the information available in relation to these criteria, limited resources, random factors and spatial constraints of varying complexity. Thus we hope to have shown in this book the interest of optimisation models in designing a network of protected areas. We also hope that the reader will not be too put off by the mathematical formalism that is needed for the presentation of mathematical programs. We hope that the very numerous examples will facilitate his/her reading.

The study of these optimization problems involves several steps: problem definition and modelling, formulation by a mathematical program, possible reformulation by a mathematical program that can be solved effectively, *i.e.*, within a reasonable computation time, pre-treatments, *i.e.*, study of the structure of the problem in order to reduce the number of variables and/or constraints, and possible improvement of the chosen formulation. There are generally several ways to model an optimization problem using a mathematical program and an important question is, therefore, to find the "right" model, *i.e.*, the one that solves the problem in a reasonable computing time while not being too difficult to interpret. These different steps are illustrated in many examples. In order to lighten the presentation and allow the reader to follow the different steps, these examples are hypothetical but generally described in detail. However, the optimisation models that are presented, even if they sometimes include simplifying hypotheses so as to not lose perspective on the proposed approach, can be applied to real-world problems. All the mathematical programs associated with these examples have been modelled using the AMPL language and resolved by CPLEX, a solver based on the most efficient algorithms available today. The experiments have been carried out on a PC with an Intel Core Duo 2 GHz processor and mainly using the solver CPLEX version 12.6. The results obtained and the study and interpretation of the solutions are presented. It is often interesting to examine several solutions of a given problem: all the optimal solutions as well as some solutions close to them. Indeed, this may allow certain criteria that are difficult to formalize to be taken into account. Performance indications such as computation times are also provided for large instances.

The whole approach described above can be an effective decision-making tool for the actors involved in biodiversity conservation policies based on the creation of protected zones. This tool does not replace the actors but can be used to recommend behaviour by clearly highlighting the consequences of the various possible decisions in relation to the objectives of these actors. It should be noted that a protected zone is envisaged on the basis of ecological objectives and criteria, but that its actual establishment depends on a number of other factors, including stakeholder-dependent economic and political ones. The significant gap between theoretical studies and practical implementations is often mentioned in the conservation literature. This gap can certainly be narrowed by establishing closer collaboration between "theorists" and "practitioners" during all the stages of a protected zone network design project.

The reader will not find in this book a study of the specific problem in which he/she is interested because the possible optimization problems, in connection with the creation of protected zones, are extremely numerous and varied. On the other hand, he/she will generally find a similar problem from which he/she can draw inspiration, thanks to the flexibility of mathematical programming, to approach his/her own. Above all, he/she will be able to find a general approach, applicable in many contexts, to address, through mathematical programming, the formulation and resolution of a specific protected zone design problem. It should be noted that there are generic tools such as C-Plan, Marxan and SITES to address these issues. These tools, often based on heuristic methods, have the advantage of being fairly general, but the disadvantage of this generality is that they may not be easily adapted to a specific context. Certainly, in many cases, specific tools need to be developed and we hope that this book will help in the design of such tools.

Plan of the Book

Each chapter deals with a particular aspect involved in the selection of a set of zones to be protected, among a set of candidate zones, and aimed at preserving biodiversity as much as possible. As already mentioned, we mainly deal with species protection in this book, but all the developments presented could be applied to other components of biodiversity. Each chapter first of all presents the interest of the aspect considered with regard to biodiversity protection and then proposes, within the unified framework of mathematical programming, models, formulations and solutions to optimization problems naturally linked to this aspect. Most of these problems are illustrated by detailed examples and numerous computational experiments to evaluate the effectiveness of the proposed approaches are presented. As mentioned, each chapter deals with a specific aspect related to the choice of a set of zones to be protected, but the concrete choice of these zones will generally have to combine several of these aspects.

Chapter 1 deals with the basic problem associated with the optimal choice of zones to be protected as well as some variants of this problem. A use of the AMPL modelling language, coupled with the CPLEX solver, is also presented.

The basic problem can be expressed as follows: what is the set of zones to be protected, among a set of candidate zones, in order to preserve biodiversity "as best as possible"? In this basic problem, we assume that, for each species considered, we know either all the zones whose protection individually ensures the protection of this species, for example its survival, or the minimal population size of this species which must be present in the reserve, *i.e.*, in the set of protected zones, for this species to be considered as protected. Protecting a zone has a cost and protecting biodiversity as best as possible can have several meanings. For example, one can seek to protect as many species as possible within an available budget or seek to protect, at a minimum, a number of species through a minimal cost reserve. A dynamic version of this basic problem, in which zones are progressively protected over time, taking into account a budget constraint related to each period under consideration, is also presented and discussed in this chapter. These elementary problems of zone selection are NP-difficult. In other words, it is conjectured that there is no polynomial-time algorithm to solve them. An algorithm is said to be polynomial in time if the number of elementary operations required to perform it can be expressed as a polynomial depending on the size of the data. However, many optimization problems related to the design of a network of protected areas, although NP-difficult, can be solved efficiently, especially through mathematical programming.

Chapters 2, 3, 4, and 5 deal with the spatial aspects of a set of protected zones.

The spatial configuration of a nature reserve – a set of protected zones – is an essential factor for the survival of the species that live there. Fragmentation, connectivity, compactness or edge length are three important and interdependent aspects of this configuration. Fragmentation is associated with the dispersion of the zones that make up the reserve (chapter 2). This dispersion often results from the fragmentation of space due to artificial phenomena such as the presence of urbanized areas, intensive agricultural areas or transport infrastructures. In contrast, in a connected reserve, all the zones are contiguous and species can circulate easily throughout the whole reserve (chapter 3). The compactness of a reserve corresponds to the distance separating the zones from each other (chapter 4) and this distance can be measured in different ways. The edge of a reserve consists of the transition zones between the reserve and the surrounding matrix (chapter 5). Urban and agricultural development as well as logging can make it difficult to build relatively compact and low-fragmented reserves. Fragmentation, combined with lack of compactness, prevents species from moving around the reserve as they should and could in a compact and non-fragmented reserve, contributing to a loss of biodiversity. Of course species are affected differently by the fragmentation and compactness of their habitat. It should be noted that the ease of movement of species within a reserve is not always without its disadvantages, as it can increase the risk of disease transmission or facilitate the proliferation of invasive species. Chapter 4 also addresses the problem of selecting a set of zones by taking into account both the connectivity and compactness criteria.

Chapter 6 deals with biological – or wildlife – corridors. These allow species to move through more or less fragmented landscapes.

Landscape fragmentation, mainly due to urbanization, agriculture and forestry, is an important cause of biodiversity loss as it prevents species from moving as they should. One of the options commonly used to establish – or restore – some connectivity between different habitat areas is the establishment of corridors. This connectivity within a landscape is considered an essential element for biodiversity conservation. Several aspects of optimal corridor design are presented in this chapter, including the restoration of an existing corridor network in order to increase its permeability.

Chapters 7, 8, and 9 deal with the choice of a set of zones to be protected in view of the inevitable uncertainties affecting the protection effects. Several ways of taking these uncertainties into account are presented.

In all the previous chapters it is assumed that the effects of protection – or not – of the different zones are perfectly known. In chapters 7, 8, and 9, we introduce the integration of a certain uncertainty in these effects. A first way to reflect uncertainty is to assume that protecting a zone ensures the survival of a given set of species in that zone with a certain probability – difficult to establish – for each of those species (chapters 7 and 9). A second way of translating uncertainty about the effects of zone protection is to consider, as before, that the protection of a zone enables the survival of certain species with a certain probability, but it is now assumed that these probabilities can be affected by errors (chapter 7). Finally, a third way to translate uncertainty about the effects of zone protection is to consider that several scenarios are possible (chapters 8 and 9). A scenario is a set of consistent hypotheses on the evolution of the direct or indirect factors that may affect the survival of the considered species. It is hypothesised that it is possible to assess the impact of this evolution. The effects of protecting a zone then depend on the scenario that occurs.

Chapter 10 concerns the choice of zones to be protected in order to maximize the phylogenetic diversity of the impacted species. This measure takes into account both the evolutionary history of the species under consideration and their kinship relationships. The information necessary to implement this approach may be relatively difficult to obtain.

Many authors suggest that the effectiveness of protected areas could be significantly enhanced by taking into account criteria other than species richness or abundance when assessing a set of species from a biodiversity perspective. An interesting measure which is increasingly being used in the field of conservation is phylogenetic diversity. It is based on the concept of the phylogenetic tree associated with the set of species considered and reflects the evolutionary history of these species and their kinship relationships. There are different ways to define phylogenetic diversity. We consider here that the phylogenetic diversity of a set of species is equal to the sum of the branch lengths of the phylogenetic tree associated with this set. Several ways of taking into account the inevitable uncertainty affecting the phylogenetic tree associated with a set of species – tree structure and branch length – are also proposed.

Chapter 11 deals with the selection of zones to be protected, based on different measures of the diversity of a set of species that have not been considered in previous chapters.

In the first part of this chapter, we examine the choice of the zones to be protected by measuring the diversity of the species thus protected by indicators other than species richness or phylogenetic diversity. We measure this diversity in three different ways: the first takes into account the dissimilarity or distance between 2 species which can be represented, for example, by the genetic distance calculated from the differences between DNA sequences; in the other two cases, we are interested in the diversity of protected species as measured by two classical indices, the Simpson's index and the Shannon–Wiener index. These two indices take into account both species richness and abundance of each species. In the second part of this chapter, we focus on the set of individuals, of a given species, concerned by the choice of zones to be protected and we measure the diversity of this set by its average kinship.

Chapter 12 takes into account an increasingly important issue to incorporate into the design of protected zones, namely climate change. Indeed, a substantial number of species can lose valuable habitat in a set of protected zones if the climate changes. We are also interested in the choice of zones to be protected in order to mitigate climate change.

Climate change appears to be an important emerging issue to be taken into account in the development of protected zones. Most of the issues discussed in the previous chapters can be re-examined in the context of climate change. Thus, the approach is illustrated by taking as a starting point some basic problems, some of which having already been discussed in previous chapters. In the context of optimal choice of zones to be protected, climate change can be taken into account in different ways: some zones are likely to protect certain species at certain times but this is no longer the case in later periods and conversely, some zones, at certain times, do not allow for the protection of certain species but will allow it in later periods; the population size of the different species considered in each zone changes over time and it is assumed that this change is known; the area of habitat favourable to a given species in a given candidate zone changes over time and it is assumed that this change is known. We also examine cases where there is uncertainty in predicting the impact of climate change, using a probabilistic approach and also a scenario-based approach. We are also interested in a dynamic choice of the zones to be protected: some zones, acquired at certain times to be protected, may be ceded in subsequent periods. Finally, in this chapter we examine a two-criterion problem consisting in selecting a reserve whose interest is assessed by the number of species it allows to protect but also by the quantity of carbon – one of the main greenhouse gases – it allows to capture and stock. Protected zones can, for example, limit the loss of forests, which is considered an important cause of climate change since forests contain the largest terrestrial carbon stock.

The appendix presents basic concepts concerning mathematical programming, graph theory and Markov chains, in relation to the content of this book, as well as references to further explore these topics. These concepts are illustrated by many examples.

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