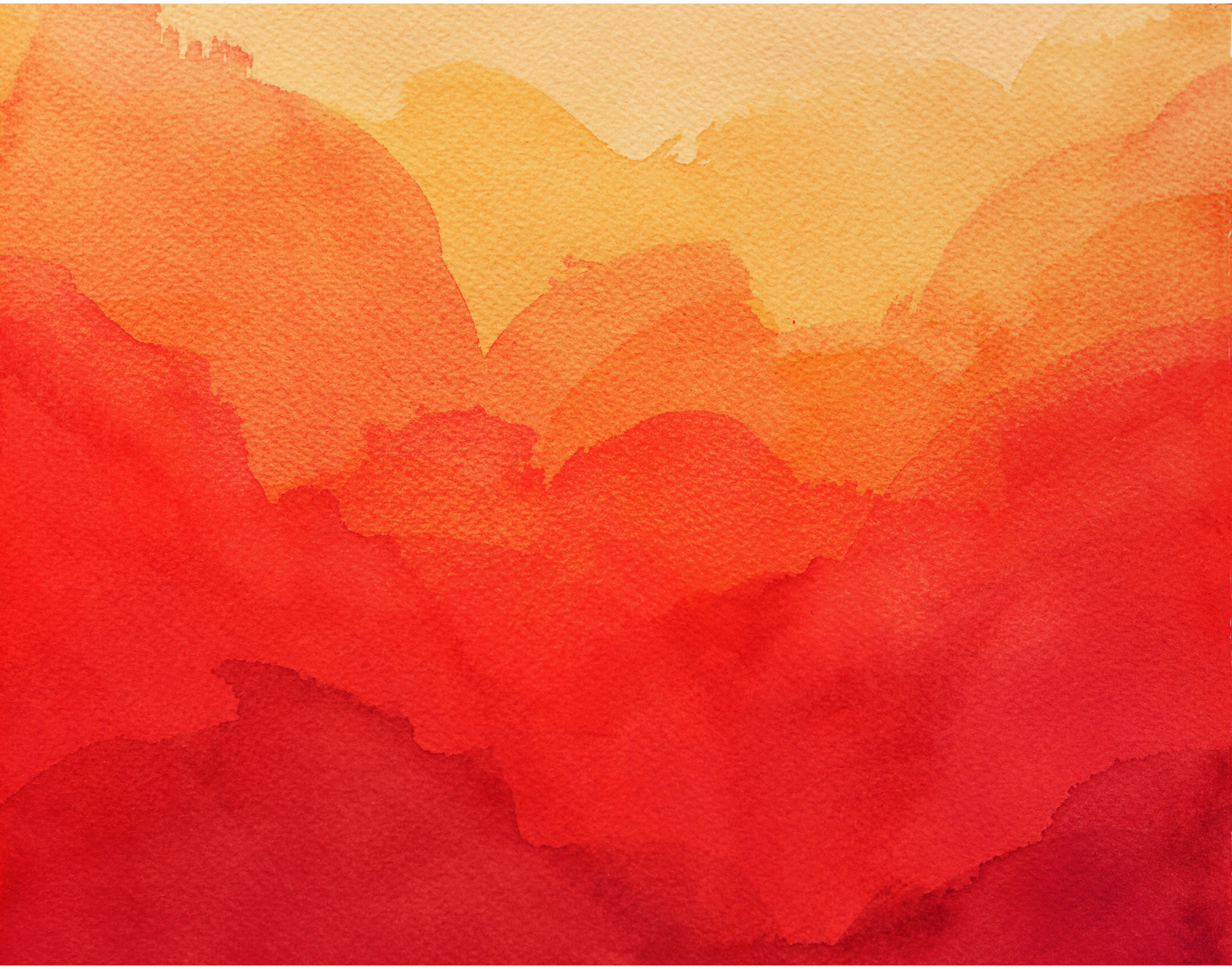
Ecological Coherence of the Natura 2000 Network

Plausible approach based on the Macaronesian Biogeographical Region



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Madrid, 2025

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Preface

This document is conceived as a concept note, hoping to serve as a reference or inspiration for readers approaching the theme of coherence of the Natura 2000 Network for the first time. Its purpose is to create a concise conceptual body, and to demonstrate its feasibility by proposing an assemblage of techniques that converge towards an evaluation procedure. Conveying the operability of the ensemble has been considered a priority, as opposed to a detailed review of its components. In other words, the choice of techniques incorporated in each component of coherence is not exclusive, and alternative models can substitute the models presented here as long as they play an equivalent role in the final result. From this point of view, virtually no part of the document replaces an in-depth review of the subject, and bibliographical references have been reduced to the minimum necessary to ensure comprehension.

Faced with the need to specify and assemble a practical approach to the coherence of a conservation network such as Natura 2000, it seemed more logical to use a particular biogeographical region as an example, rather than to discuss general problems. The Macaronesian Region is unique in this respect, because its island dimension adds interesting theoretical opportunities, not only related to the persistence of habitats and species, but also to methodological aspects such as the relationship between spatial scale and size of the study area. However, even with this as a common thread, previous experience with the methods discussed in this and other regions is limited. This explains why many of the examples developed come from other biogeographical regions, and why this document should not be taken as a protocol for assessing the coherence of the Natura 2000 Network in the Macaronesian region in particular

While the authors have made a special effort to explain the techniques in a concrete and reproducible way, this is less true for the administrative and managerial aspects. The reason is that the concept of network coherence can be given a theoretical basis, for the testing of which objective techniques can be specified. However, management, and particularly its interface with a technical component, is more of a heuristic problem than a theoretical one. In other words, a prototypical relationship between conservation policy-makers, managers and technicians must be established, establishing functional feedback between these three types of actors. This is easier said than done, as the interests and constraints of each type come from different worlds and logics. Therefore, interactions must be refined during the solution of a problem. The expected contribution of this paper is to provide seeds for such interactions, so that heuristic refinement can be achieved on a solid and explicit basis.

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Gabriel del Barrio

1. Introduction

1.1. Background

Biodiversity and natural and semi-natural landscapes have been under serious threat since the onset of the Industrial Revolution. This milestone marked the development of natural resource exploitation and transformation processes that profoundly changed the landscape in terms of intensification of use, fragmentation and pollution. Generally speaking, these forces of change were initiated gradually in multiple locations, and their effects eventually coalesced into a spatial structure that tended to leave the initial, previously dominant landscapes as islands within artificial landscapes of varying degrees of alteration.

The Western societies that gave rise to the Industrial Revolution, through their ability to drag it into other areas (whether by colonisation or emulation) spread this issue all over the planet. This led to conservation policies aimed at conserving the biodiversity and ecosystems of concern, which were beginning to be perceived as vulnerable to the intensity of global change thus unleashed. This in turn gave rise to protected areas, which have become one of the most effective measures for biodiversity conservation.

At present, conservation scenarios share, in varying proportions, attributes of two extreme manifestations of spatial change. On the one hand, there is the more resilient situation, where landscape and natural ecosystem reserves cover large areas of land that (probably) exceed the area necessary to ensure the stability of the ecosystems concerned. Focusing on terrestrial environments, two examples are The Kavango Zambezi Transfrontier Conservation Area, Zambia, Botswana, Namibia, Zimbabwe, and Angola (519,912 km^2) or the Yukon Delta National Wildlife Refuge, Canada (77,538 km^2). Such sizes do not in themselves guarantee the survival of the ecosystems they contain, but at least it can be assumed that the genetic and trophic resources necessary to withstand disturbance are contained within the preserved space.

At the other extreme, are the relatively small reserves that preserve bits of relict landscape, intermingled within a profoundly transformed territorial matrix. The largest examples in Spain are the national parks of Picos de Europa (647 km^2) and Doñana (543 km^2), but in Europe as a whole, national parks with areas of just a few square kilometres are not uncommon.

Islands, due to their spatial configuration, are a specific example of the second type of scenario. Here, the necessarily small reserves are surrounded by marginal territory with varying levels of artificialisation. For example, in Madeira there are reserves as small as the Cabo Girão Protected Area (3.15 km^2), and others comparatively similar in size to mainland reserves, such as the Parque Natural da Madeira (444 km^2). In all of them there is a high contrast between protected and unprotected territory due to the degree of occupation of the latter, and the solution tends more to increase the amount of protected territory (58% of the land area in Madeira) than to reduce this contrast.

The need to conserve biodiversity in these two types of scenarios has influenced the scientific and technical approaches developed respectively. In the first type of scenario, the figure of the national park as a large self-contained reserve prevailed. The case of Yosemite National Park in the USA was the first, and is still paradigmatic: European settlers in the mid-19th century were fascinated by the aesthetic and natural values of the area, and pushed for a legal concept that would ensure its conservation. Having no particular space limitations, 3,074 km^2 were designated for this purpose.

Classical scientific approaches to optimising conservation targets were strongly influenced by such scenarios. Thus, in general, they tended to prioritise species representativeness over site availability, assuming that identifying and designating sites would be a secondary problem (Margules et al., 1988). This paradigm gave rise to two important conceptual advances, optimality and complementarity. The concept of optimality was developed in this context, defining it as the maximum efficiency of representation in terms of the amount of land protected (Pressey and Nicholls, 1989). On the other hand, the principle of complementarity (Faith et al., 2003) evaluates new stock additions by their ability to complement, rather than duplicate, the properties of existing stocks given conservation targets. This led to the development of mathematical methods for semi-automatic selection of nature reserves, such as heuristics (Pressey et al., 1996). These methods found their greatest challenge in solving the problem of optimality, assuming that the size of the territory from which to extract an efficienti

collection of reserves did not impose practical constraints. Consistently, the fields of study that fed into these studies were often in North America, South Africa or Australia.

Neither the methods based on large national parks nor those based on optimised conservation reserves had much application in the second type of scenario. For example, the national parks declared in Spain form a heterogeneous set of landscape extractions based on uniqueness, and their extensions alone would probably not be able to guarantee the conservation objectives set at the time of declaration. Regarding the objective optimisation of reserves, the amount of land available, both for natural values and for exploitation rights, is so small in this type of scenario that the problem is more often to protect what is left than to mathematically optimise a minimum selection.

The Natura 2000 Network was the European response to the need to preserve biodiversity. Three factors influenced its inception: the conceptual seeds developed by the Australian school of conservation (even if their application was not direct to the European case), the findings described in the previous paragraph, and the integrative impulse of a relatively young European Union. The Natura 2000 Network was born as a cohesive pan-European system of conservation reserves, explicitly distinguishing between sites, habitats and species, and was mandated from the outset to be coherent. Its precursor was the European Biotopes/CORINE Programme, which emerged in the late 1980s with the aim of establishing an EU-wide inventory of major natural sites.

In practice, the growth and development of the Natura 2000 Network has been bottom-up rather than top-down. In other words, rather than looking for reserves with which to optimise the representativeness or complementarity of the selections, sites were designated opportunistically. Their incorporation into the Natura 2000 Network depended on what remained available as natural territory, on the ownership of the land and on the attitude of the economic agents involved. It should be noted that European territory in general has been densely inhabited for many centuries. This means that most of its landscapes have gone through cycles of exploitation-abandonment, and that the notion of pristine environment barely exists, only in small and inaccessible locations.

The Natura 2000 Network grew more by accretion than by planning. In spite of this, in a few years it reached significant sizes within all EU countries where, altogether, it consists of 27027 sites accounting for 18.6% of the territory. In Portugal, the Natura 2000 Network is made up of 167 sites representing 20.6% of its national territory, figures which, in Spain, increase to 1858 sites and 27.3% of the territory. Regarding the Macaronesian Biogeographical Region, the Autonomous Region of Madeira [Portugal], currently contains 19 sites, representing 32% of its land area; the Autonomous Region of the Azores [Portugal] is made up of 41 sites covering 15% of its land area; and the Autonomous Community of the Canary Islands [Spain] has 188 sites covering 38% of its land area. These figures suggest that the Natura 2000 Network has completed its sufficient collection aspect, in respect of which it can be diffusely assumed to meet its conservation objectives.

1.2. Problems

The Natura 2000 Network currently consists of a set of conservation reserves embedded in a highly altered and socio-economically dynamic territorial matrix. Although the aggregate amount of territory is large, these reserves have rather small sizes and arbitrary distances between them, in a fragmentation that certainly does not facilitate their individual survival. It is therefore urgent to define the Natura 2000 Network as a system and to assess its coherence, developing the initial mandate of the Habitats Directive which recognised that the network as a whole would only be stable if transfers, redundancies and complementarities between protected sites were formalised and promoted.

It is interesting to note that, despite the unanimously recognised need to define the Natura 2000 Network as an interconnected system, very limited formal progress has been made in this regard. Ecological connectivity has received much attention in this context. The basis for this is that, by referring to transits of wild species through the landscape, it has a skeletal potential for the Natura 2000 Network as a whole, allowing distant network elements to be linked through the unprotected landscape matrix

Thus, ecological connectivity has been recognised as an essential property of conservation networks [Gurrutxaga et al., 2010], and specific territorial policies have even been suggested to favour it in Europe through the Natura 2000 Network [Kettunen et al., 2007]. However, specific proposals that go beyond the local level are relatively rare. In the case of Spain, Marquez Barraso et al., [2015] modelled the connectivity of 33 regional habitats for the whole peninsular territory, defining corresponding networks of corridors that explained connections between the different populations. Also using vegetation types, but in this case as indicators of animal movement, WWF Spain [2018] proposed 12 green corridors that would facilitate the mobility of certain emblematic species of flora and fauna.

These studies, based on specific habitats or species, were joined by others that simply assessed the spatial continuity or fragmentation of certain landscape types, without defining specific connectivities, on the assumption that this would globally favour the transit of protected taxa. The study by Estreguil et al., [2013] on forest pattern continuity using the methodology developed by the EC Joint Research Centre is a recent development of this trend. Thus, connectivity has been adopted for the generation of a coherent and planned network through various national strategies developed by EU Member States. One of these is Green Infrastructure, consisting of a planned network of natural and semi-natural areas designed to promote a wide range of ecosystem services and also to enhance biodiversity. Green Infrastructure is structured around the Natura 2000 Network.

The above examples are only intended to give a representative, but not exhaustive, idea of connectivity applications to the Natura 2000 Network. Developments on habitat or species issues in a given territory has been solid and, although fragmentary, mark a consistent line of spatial analysis.

However, the original intention of using connectivity to systematise the territorial structure of the Natura 2000 Network as a network remains unconsolidated. There are several reasons for this.

Firstly, the connectivity studies thus approached are multiple, and the overlapping of a number of individual solutions rarely leads to an integrated solution. In other words, the more works on connectivity applied to specific taxa appear, the more difficult it is to organise them into a synthetic proposal, as these studies lack a shared spatial structure. This paper explores the definition of the Natura 2000 Network as a network using its conservation reserves as nodes, so that it is possible to add an indefinite number of connectivity works, with the only desirable effect of increasing the complexity of the relationships between nodes.

Secondly, the trans-territorial nature of connectivity contrasts with the almost fractal fragmentation of competences in the hierarchy of administrative spheres. Spain can examine its connectivity networks, but by not doing so jointly with Portugal, the border between the two countries is populated by modelling artefacts. Within Spain, each autonomous community establishes its own connectivity networks, which systematically ignore what happens for the same taxon just across the border with the neighbouring autonomous community. This creates

a chaos of concentric hermetic areas which makes any integration at a given organisational level impossible and which, contrary to what is desirable, spreads from the lower levels of administrative management [NUTS 3, 2 and 1] to the higher level of bio-geographical region, where it is impossible to obtain an overall view. This paper proposes explicit couplings between technical analysis and management levels, so that information can flow through the respective hierarchies without loss or distortion.

In addition, and contrary to initial expectations, it is considered that connectivity alone is not sufficient to form a conservation network or to assess its coherence. For instance, a basic objective of conservation is to preserve biodiversity and associated ecological functions, and to this end it is essential to consider representativeness. In doing so, it is necessary to take into account that the designated populations have a reasonable capacity to respond to external disturbances, and their resilience should be indicated. In other words, not only do additional properties emerge alongside connectivity, but their integrated consideration in defining and assessing the coherence of the Natura 2000 Network can be anticipated.

1.3. Objectives

The general objective of this document is to create a conceptual and methodological framework for assessing the coherence of the Natura 2000 Network in the Macaronesian Region.

The specific objectives are to:

I. Establish an operational definition of coherence that can be practically implemented using explicit components, and that is aligned with European conservation policies.

II. Identify appropriate information and tools to enable a harmonised assessment of coherence components. The information will be based on data products managed by institutional bodies to ensure long-term monitoring. The tools will be based on open licences to encourage the adoption of the approach by interested public administrations.

III. Develop a planned management system, which makes it easier for the administrations in charge of the Natura 2000 Network to maintain the coherence of the Network. This system will be based, at least, on the differential character of each site and the establishment of conservation objectives at Network level.

2.Operational definition of coherence

2.1. The Natura 2000 Network

Directive 92/43/EEC [Habitats Directive] aims to contribute to the preservation of biodiversity through the conservation of natural habitats and of wild fauna and flora in the European territory of the Member States to which the treaty applies. "Natural habitats" means terrestrial or aquatic areas differentiated by their geographical, abiotic and biotic characteristics, whether they are entirely natural or semi-natural.

Measures taken pursuant to that Directive shall also be designed to maintain or restore natural habitats and wild species of fauna and flora of Community interest to a favourable conservation status.

In this sense, Natural Habitat Types of Community Interest [HCIs] are habitat types that i] are in danger of disappearance in their natural range, ii] have a small natural range [due to regression or intrinsically restricted area] or iii] are representative examples of typical features of one or more biogeographical regions.

Similarly, Species of Community Interest [SpCI] are those that are [i] endangered, [ii] vulnerable, [iii] rare [small populations] or [iv] endemic and requiring special attention.

Priority natural habitat types are those habitats under threat of disappearing and whose conservation places a special responsibility on the Community, given the importance of the proportion of their natural range included in the European territory. Similarly, priority species are those whose conservation also entails a special responsibility for the same reason.

On the other hand, the "conservation status" of a natural habitat will be considered "favourable" when:

- Its natural range and areas it covers within that range are stable or increasing.
- The specific structure and functions which are necessary for its long-term maintenance exist and are likely to continue to exist for the foreseeable future.
- The conservation status of its typical species is favourable.

Similarly, the "conservation status" of a species shall be considered "favourable" when:

- Population dynamics data on the species concerned indicate that it is maintaining itself on a long-term basis as a viable component of its natural habitats.

- The natural range of the species is neither being reduced nor is likely to be reduced for the foreseeable future.

- There is, and will probably continue to be, a sufficiently large habitat to maintain its populations on a long-term basis.

Article 3 of this directive deals with the establishment of the Natura 2000 Network: A coherent European ecological network of special areas of conservation shall be set up under the title Natura 2000. This network, composed of sites hosting the natural habitat types listed in Annex I and habitats of the species listed in Annex II, shall enable the natural habitat types and the species' habitats concerned to be maintained or, where appropriate, restored at a favourable conservation status in their natural range.

The Natura 2000 network shall include the special protection areas classified by the Member States pursuant to Directive 79/409/EEC.

In this context, Site of Community Importance (SCI) means a site which, in the biogeographical region or regions to which it belongs, contributes significantly to the maintenance or restoration at a favourable conservation status of a natural habitat type in Annex I or of a species in Annex II. It may thus contribute significantly to the coherence of Natura 2000 referred to in Article 3, and/or contributes significantly to the maintenance of biological diversity within the biogeographical region or regions concerned.

Similarly, Special Area of Conservation (SAC) means a site of Community importance designated by the Member States through a statutory, administrative and/or contractual act where the necessary conservation measures are applied for the maintenance or restoration, at a favourable conservation status, of the natural habitats and/or the populations of the species for which the site is designated.

Each Member State shall contribute to the creation of Natura 2000 in proportion to the representation within its territory of the natural habitat types and the habitats of species. Where they consider it necessary, Member States shall endeavour to improve the ecological coherence of Natura 2000 by maintaining, and where appropriate developing, features of the landscape which are of major importance for wild fauna and flora, as referred to in Article 10. These are those elements that are essential for the migration, geographical distribution and genetic exchange of wild species because of their linear and continuous structure, or because of their role as linking points.

It is worth mentioning that the impact assessment of plans and projects not related to the management of the site should take into account the conservation objectives of each site. Furthermore, the competent national authorities shall agree to such a plan or project only after having ascertained that it will not adversely affect the integrity of the site concerned. Article 4(4) also highlights the priority of designating a site as a SAC " in the light of the importance of the sites for the maintenance or restoration, at a favourable conservation status, of a natural habitat type in Annex I or a species in Annex II and for the coherence of Natura 2000, and in the light of the threats of degradation or destruction to which those sites are exposed".

The implementation of Directive 92/43/EEC therefore involves three basic elements associated with their respective conservation objectives:

• habitats and species of Community interest: maintaining (or restoring) a favourable conservation status;

• each designated Special Areas of Conservation: maintaining their integrity; and

• the whole of the SACs (the Natura 2000 Network): protecting coherence

Although Article 1 of the Habitats Directive contains definitions relating to habitats (HCI) and species (SpCI), favourable conservation status and sites or Special Areas of Conservation (SAC), it does not include any reference to the concept of integrity or the concept of coherence. The latter is only associated with two clear elements: representation and landscape elements, i.e. what can be called connectivity.

In fact, the construction of the Natura 2000 Network has basically been based on the concept or component of representation of habitat types and species of Community interest using, as the main criterion, threshold values or percentages of inclusion to establish a diagnosis of sufficiency of representation.

In the case of Spain, the representation component was applied, for each of the four biogeographical regions, to the group of protected natural areas designated by the different regional administrations. For HCIs, representation was assessed using specific threshold values for each habitat type based on two variables: occupied area and designation as a priority habitat type. For species, the degree of national threat was also taken into account. With regard to the Macaronesian Biogeographical Region, the procedure for assessing representation was carried out systematically for each of the islands, taking into account the role of each of them in the Canary Islands archipelago as a whole [Orella et al., 1998].

Three decades after the Habitats Directive was adopted, it remains to be assessed whether the Natura 2000 Network is fulfilling its primary function, i.e., maintaining habitat types and species of Community interest at a favourable conservation status. In other words, it remains to be seen whether the Natura 2000 Network, especially at the level of the individual Community Biogeographical Regions, is truly coherent.

In order to assess the coherence of the Natura 2000 Network in a standardised way, it is necessary to establish an operational definition of the concept and to develop methodologies and tools that allow this to be done in a rigorous and objective manner, identifying the differential role or function that each SAC has in maintaining this coherence. This document represents a significant step in this direction.

2.2. Definition of coherence

The Natura 2000 Network was conceived from the outset as a conservation network, with the aim of conserving biodiversity at the European level by preserving populations of Species and Habitat types of Community Interest [SpCIs / HCIs] located in Special Areas of Conservation [SACs].

In a broad sense, a conservation network consists of a set of elements [e.g., protected areas] that interact with each other to synergistically achieve an overall objective on a larger scale than the simple sum of their respective attributes. The relationships between protected areas that substantiate these interactions are a measure of the coherence of the network.

As noted in the previous Section, the notion of coherence currently remains a diffuse guideline for the management of the Natura 2000 Network, despite having been explicitly mentioned in the creation and development of the Network. It is therefore necessary to use a definition that is conceptually sound and allows the objective implementation of the techniques necessary for its verification.

The working definition proposed by Catchpole [2013] has been adopted here:

> An ecologically coherent network consists of designated sites for the protection of relevant habitats and/or species; it should support habitats and populations of species in a favourable conservation status throughout their natural range [including unprotected territory and marine areas beyond Natura 2000 sites]; and contribute significantly to the biological diversity of the biogeographical region. At the scale of the whole network, coherence is achieved when: the full range of variation of valued characteristics is represented; these characteristics are replicated at different sites over a wide geographical area; dispersal, migration and genetic exchange of individuals is possible between relevant sites; all critical areas of rare, highly threatened and endemic species are included; and the network is resilient to disturbances caused by natural and anthropogenic factors.

This simple definition represents an important step forward, as it considers the Natura 2000 Network as a system, whose coherence depends on five properties that converge towards the stated conservation objectives: representativeness, redundancy, connectivity, rarity and endemism, and resilience. Coherence thus emerges as a meta-property of the Natura 2000 Network.

2.3. Spatial reference units and domains

The above working definition clarifies an aspect that is as obvious as it is overlooked in its implications: a network consists of sites. In other words, the spatial unit of reference for the Natura 2000 Network is the SACs. If the Natura 2000 Network were visualised as a network graph, the SACs would constitute the nodes, and the five properties related to coherence should be attributed either to nodes or sets of nodes, or to the edges that relate them.

For example, in this scheme, representativeness must be elementally attributed to each SAC, according to the habitats and species it contains. The SACs can then be grouped together depending on the problem in question. For example, the representativeness of the abiotic environment can be assessed for one SAC, for all SACs at a certain administrative level [e.g. NUTS 2] or for the whole biogeographical region. The foregoing is also true when assessing the representativeness of the Natura 2000 Network for a certain HCI or SpCI, which can be obtained by grouping their populations at the appropriate level of organisation.

Connectivity is rather an attribute that relates SACs to each other, and therefore corresponds to the edges of the visualised network graph. In the simplest case, two SACs are related to each other when they contain two populations of a certain HCI or SpCI connected to each other. The relationship is directional and can be quantified, for example, as the cumulative friction [cost distance] in the shortest corridor linking these populations.

This procedure can be increased as much as necessary. Thus, using connectivity to represent all SACs containing populations of an HCI or SpCI will give a realistic idea of the contribution of the Natura 2000 Network to their conservation. And showing the connectivity relationships between all SACs using HCIs and/or SpCIs in a given spatial domain will come very close to a systemic notion of the Natura 2000 Network.

The consideration of coherence in SACs has some implications not included in the current management of the Natura 2000 Network. It is true that the SACs are management units from an administrative point of view, and all of them have management plans that regulate the activities and interventions within their boundaries. However, redundancy or complementarity relationships between SACs are not part of such plans, and most studies on HCIs and SpCIs are still carried out on the entire distribution in an area of study, rather than taking the subset of the distribution contained in the Natura 2000 Network as the subject of work.

For example, the connectivity study by Marquez Barraso et al., [2015] modelled 33 zonal HCIs including dominant woodland and shrubland formations in mainland Spain. Populations that defined each connectivity problem were produced from the full observed distribution, and modelling yielded green corridor networks for each HCI studied. The contribution of the Natura 2000 Network to the connectivity of each case was assessed by identifying the part of their network that was included in the Natura 2000 Network. This approach has recently been repeated for 31 forest types, with improved input data, in a project commissioned by the Spanish Ministry for Ecological Transition and the Demographic Challenge [MITECO] and funded by Tragsatec. We can therefore assume that there is a consistent need for studies of this nature.

Such studies are of objective value for understanding the forest ecology of individual formations, and are an important support for managing the territory where they are located. Furthermore, their contribution to the definition and assessment of the Natura 2000 Network as a conservation instrument is very limited, as the connectivity networks associated with the different types of HCIs lack common or shared elements, and are therefore incommensurable.

In addition, the value of such studies for the conservation of HCIs or SpCIs is questionable. The elemental purpose of a conservation network is to be self-contained and resilient to disturbances, in such a way that the resources for this are found within the network itself. The only way to assess whether the network fulfils its role is to examine the properties referred to in the working definition [representativeness, redundancy, connectivity, etc.] within it.

In other words, only HCI and SpCI populations contained in SACs should be counted. Everything outside it is contingent, and no essential support can be expected from it. If an outside population is identified as fulfilling an important role within one of the coherence properties, it makes sense to include it in the Natura 2000 Network, not to treat it as an exception. The fact that Natura 2000 sites comprise such a large percentage of the territories of EU countries shows that this aspect was implicitly considered from the outset. However, incomprehensibly, it tends to be forgotten once the raw material of the Natura 2000 Network has been set aside and its roles are to be examined.

If it is agreed that the spatial units of reference for the Natura 2000 Network are the SACs, it is technically relatively simple to assess network properties at successive levels of organisation. From a management point of view, this implies not drastic but important changes. At present, SACs are managed as individual and internally heterogeneous spaces, which are managed individually and grouped at the required level of administrative organisation. This kind of grouping hardly allows for counts of areas and quantities of HCIs and SpCIs, which helps statistics, but is of little use for the purpose of managing the coherence of the whole.

If explicit relations between SACs (in terms of the properties defining coherence) were added to this, the result would be richer. Each SAC should have associated formal information on other SACs to which it is related, so that its consultation immediately shows information on its role in the Natura 2000 Network within the administrative domain in which it is made. Again, visualising this approach using a network graph makes it easier to understand.

In any case, each administrative level present in a biogeographical region has been relatively autonomous in choosing the number and extent of sites to be part of the Natura 2000 Network, which introduces a certain arbitrariness that may result in different assessments of coherence. Considering properties such as connectivity and resilience, the result is not the same if the Natura 2000 Network is composed of small sites with a single type of HCI in their distribution at a given time (when the Natura 2000 Network was created), as if it is composed of large sites with representation of several types of HCI in different conservation statuses. The bias implicit in these choices must be further determined.

3. Components of coherence: definitions and implementation

3.1. Representativeness

The basic purpose of any conservation network is to reserve a group of sites that reproduce the characteristics of the general territory to be preserved. From this point of view, such a group must be a representative sample, in the statistical sense, of such characteristics. Note that this representativeness refers to conservation objectives, and may be biased towards the whole territory depending on whether the common or the exceptional characteristics are favoured.

Against such systematic planning assumptions [Margules and Pressey, 2000], more often than desirable, the declaration of protected areas has followed criteria based primarily on socio-economic or aesthetic purposes, identifying sites that are unlikely to conflict with competing land uses, rather than on scientific or conservationist reasoning [Joppa and Pfaff, 2009]. The general bias towards low-cost conservation and indifference to biodiversity represents a major constraint to conservation efforts whose primary aim is to halt biodiversity decline. This has resulted in a network of spatially fixed and unconnected protected areas, overlooking the fact that they must guarantee the integrity of ecosystems.

The basic concept of representativeness usually refers to the biotic part of the territory. It is oriented to contain certain groups of living things, either directly in terms of individual species, or indirectly through habitats or communities that define landscape types and support multiple species of interest.

However, referring conservation only to the biotic part implies the assumption that the environment is stable and that the biota conserved will be persistent within the designated reserves. This is not sustainable in a scenario of global change, in which the climate is changing at variable rates that may exceed the adaptive capacity of species [Mingarro and Lobo, 2021], and anthropogenic changes are progressively fragmenting and isolating natural environments. It is therefore necessary to additionally represent in the network the environmental factors that control the presence of the living things and ecosystems to be conserved.

Biotic and abiotic representativeness can be assessed independently, but it makes more sense to do so in an integrated scheme because it maintains a correspondence between the biota and the environmental variation found in a given habitat type or region. [Austin and Margules, 1986] proposed five requirements for this:

- The target conservation entities must be clearly defined. In the case of the Natura 2000 Network, these are the Habitat Types of Community Interest [HCI] and Species of Community Interest [SpCI], specified respectively in Annexes I and II of the EU Habitats Directive.
- The spatial sampling units must be specified. In the case of the Natura 2000 Network, these are the Special Areas of Conservation [SACs].
- The territory must have a hierarchical environmental stratification or classification, which allows spatial scales and levels of conceptual aggregation to be coupled. This implies using climatic or other regionalisations.
- There is a need for an objective allocation method that relates spatial sampling units to environmental regionalisation. In relation to Natura 2000, this means establishing the extent to which the group of SACs represents the environmental variation at a given level of grouping [biogeographical region, NUTS 1, etc.].
- Finally, the representation measure must be transformed into an assessment of whether the conservation objectives are being met.

3.1.1. Abiotic representativeness

The overall objective of abiotic representativeness is to assess whether the Natura 2000 Network harbours a representative sample of the ranges of environmental variation existing in a certain spatial domain. The latter can be any NUTS level or biogeographical region, and the hierarchical nature of these grouping levels requires that environmental variation be valued consistently with it. In practice, this means that the whole territory must be subject to a classification in which there is a coupling between subdivisions [or groupings] of classes and parts of the territory.

Stratification methods based on expert knowledge are usually accurate in identifying broad classes, but imprecise in identifying transitions between them, and for the same reason, they can only subjectively assess the representativeness of specific territories against the classes thus defined.

The most objective and repeatable procedure for environmental regionalisation is a numerical classification. This makes it possible to process large masses of data, to incorporate explicit hierarchies, to measure the intensity with which a certain object is assigned to its class, and even to add new territories to an existing classification. Classical numerical taxonomy procedures have the additional advantage of being transparent, as the operator always has access to interpret each step of the process.

Paradoxically, numerical classification methods have their greatest drawback in their processing power. There is a temptation to consider them as black boxes, into which multiple variables, heterogeneous in scale and nature, are introduced in order to produce a purportedly ideal classification, which considerably reduces the usefulness of the result for understanding the territory.

Any multivariate method prioritises variables by their ability to explain the variation found in the data. When these are spatial, the said explanatory power is related to the relationship between the size of the area of study and the length of the gradients represented in each variable. Thus, in a relatively large territory, climatic variables prevail over topographic variables in forming environmental classes; conversely, in a small territory, climate [except for microclimate] is relatively constant, and topography may be more effective in describing environmental variation. Mixing both types of factors in the same classification risks introducing noise and underestimating the importance of the type less adapted to the size of the area of study.

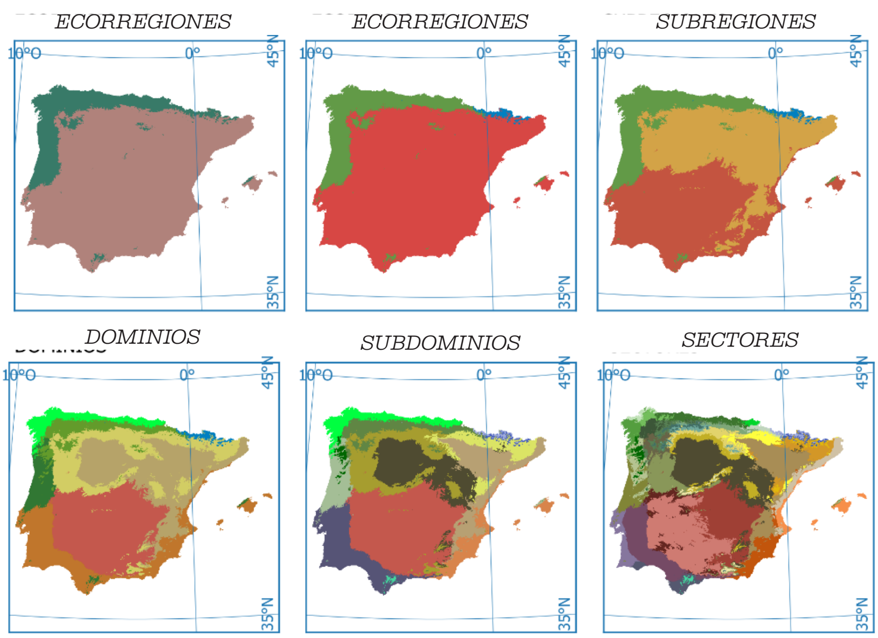
Separate thematic regionalisations are therefore often preferable to attempting a more general one, where there is a risk that variables with larger scale lengths will mask the effect of more local, but perhaps equally important, variables.

As a specific example, the following is a summary of the procedure followed to make a hierarchical climate regionalisation in a relatively large territory such as the Iberian Peninsula [del Barrio et al., 2019]. This case is similar to many others where the large size of the database does not allow the direct application of hierarchical rankings based on dissimilarity matrices. To address this here, the numerical taxonomy procedure combined two polythetic agglomerative classifications: an initial non-hierarchical classification of all objects (raster cells), and a hierarchical classification of the resulting classes.

The procedure was performed using the **PATN** package (Belbin and Collins, 2009):

1. A set of individual variables describing the climatic variation in the area of study was obtained. The WorldClim global database (Fick and Hijmans, 2017) has a spatial resolution of 30 arc seconds (approximately 926 m) and contains 19 bioclimatic variables selected from the 35 originally described by Hutchinson (Booth et al., 2014). Bioclimatic variables combine seasonal extremes of temperature and precipitation and have an important predictive power on zonal vegetation distribution.
2. Non-hierarchical classification of all raster cells according to their values for the 19 bioclimatic variables. The initial number of groups only had to meet the condition of slightly exceeding the number of configurations predictably needed to describe the variation in the study area. For this case, 60 groups were specified. The measure of dissimilarity chosen was the Gower's distance index, which linearly assesses the differences between objects described by quantitative variables. The selected classification algorithm, ALOC (Belbin, 1987), converges iteratively to a stable set of groups starting from an initial arbitrary selection of objects that are taken as seeds.
3. Extraction of the median centroids of the 19 bioclimatic variables for each of the 60 non-hierarchical groups. This produced a new, much easier to handle data set of 19 variables for 60 observations.
4. Hierarchical agglomerative merging of the 60 new objects, using an appropriate algorithm such as UPGMA and, again, the Gower's distance as dissimilarity index.
5. Visual inspection and cuts of the resulting dendrogram at appropriate levels, thus defining successive groupings of the non-hierarchical groups. This step defines the hierarchy of regionalisation.
6. Expansion of non-hierarchical group classes to raster cell classes, using the inclusion relationship of cells in non-hierarchical groups found in Step 2.

Figure 1 shows the result of this exercise. In general with such techniques, the spatial autocorrelation of the input variables ensures the spatial continuity of the resulting classes, resulting in interpretable maps.



Nivel 1: Ecoregiones	Nivel 2: Ecoregiones	Nivel 3: Subregiones	Nivel 4: Dominios	Nivel 5 Subdominios	Nivel 6 Sectores
0201 Eurosiberiana [iberoatlántica]	0301 Atlántica	0401 Atlántica	0801 Atlántico litoral o colino		
			0802 Subatlántico montano cantábrico		
			0803 Subatlántico lusitano		
0202 Mediterránea	0302 Alpina [pirenaica]	0402 Alpina [pirenaica]	0804 Alpino [pirenaico]		
	0303 Mediterránea	0403 Submediterránea	0805 Submediterráneo húmedo [montano]		
			0806 Submediterráneo continental [semiárido]		
					3627 Depresión Ebro y páramos Albacete
					3628 Sierras litorales catalana y alicantina
		0404 Mediterránea	0807 Mesomediterráneo [subtermófilo manchego extremadurense]		
			0808 Termomediterráneo	1413 Seco	
					3633 Murciano almeriense
				1414 Húmedo	

Figure 1. Climatic regionalisation of the Iberian Peninsula for the period 1981-2010. Levels 1 - 4 represent successive groupings of the whole territory at the top of the class hierarchy. Levels 5 and 6 correspond to individual low-level classes that were considered appropriate to individualise within other higher classes due to their climatic peculiarity. [Adapted from del Barrio et al., (2019)].

As mentioned above, regionalisations can be of any type as long as they combine an appropriate set of variables and respect the constraints imposed by their scale length. For example, Figure 2 shows a topographic regionalisation of the Sierra de Gádor, in the southeast of the Iberian Peninsula. The procedure followed to make it was as described above, except that the variables in Step 1 result from the geomorphometric analysis of a Digital Elevation Model at 10 m resolution, following the methods of [Xu *et al.*, 1993], and that the number of initial non-hierarchical groups was 35.

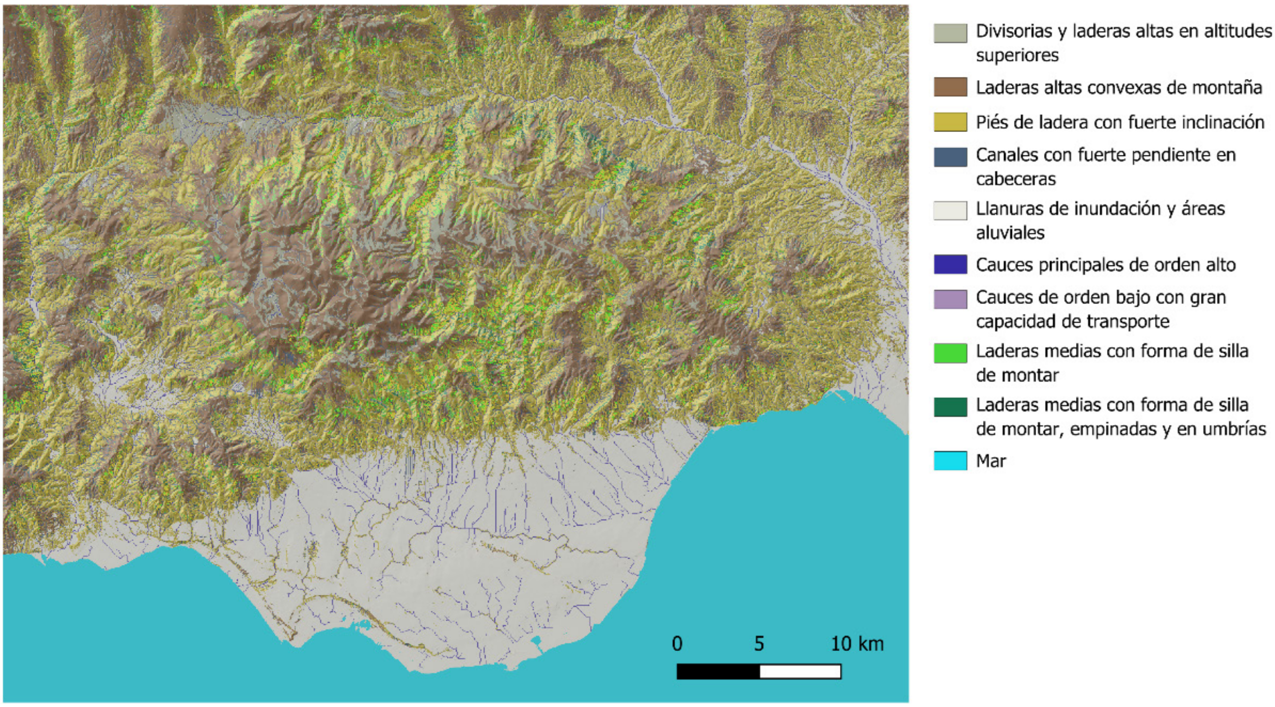


Figure 2. Topographic regionalisation of the Sierra de Gádor, SE Iberian Peninsula. The input variables resulted from the analysis of a Digital Elevation Model at 10 m resolution, and were: slope [SLO], profile curvature [PFC], plan curvature [PLC], drained uphill area [SIZ], wetness index [ATB=ln[ARE/tan[SLO]]], slope length factor[LSF=[-SIZ/22.13]0.6 - [sin SLO/0.0896]1.3], distance to the nearest watercourse [STRD] and solar exposure index [SUN, from slope and orientation and referred to a horizontal surface].

Numerical regionalisations such as those presented herein have the advantage of allowing the affinity of entities [individual cells, or groups of cells] to the defined classes to be assessed in terms of the same dissimilarity index that was used to perform the classification in the first place [Figure 3]. This yields an ideal quantitative value to be used as a measure of representativeness. For example, the climatic representativeness of sets of SACs, of individual SACs, or even of individual cells, can be measured using the relevant values of the Gower's distance index, which represent in this case the distance between each object and the centroid of the class to which it belongs. Therefore, this measure is inversely proportional to how typical [representative] the object under consideration is. Additionally, this same technique can be used to assign a regionalisation class to areas that were not included in the regionalisation at the beginning.

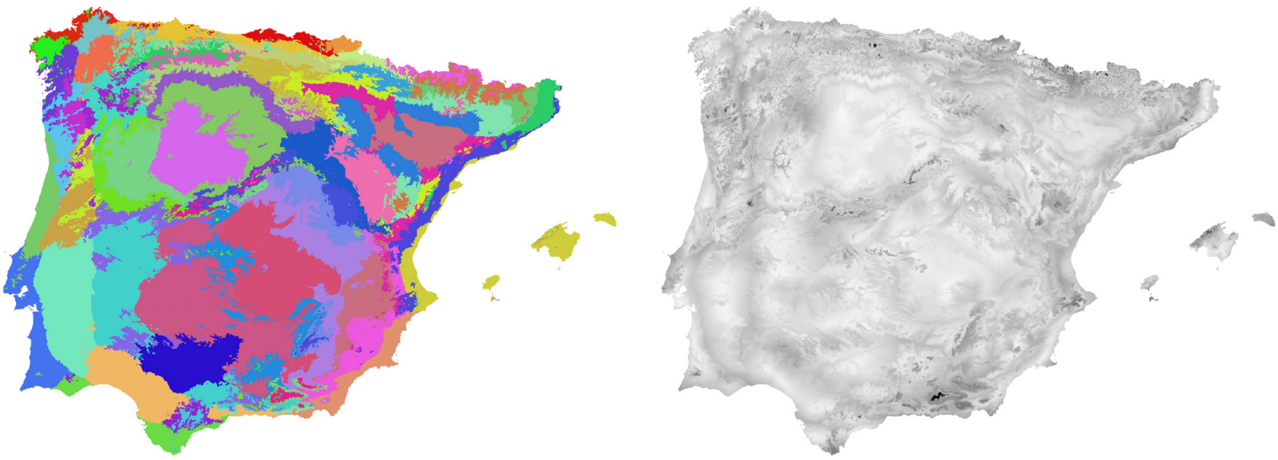


Figure 3. Classification of climate into 60 non-hierarchical groups using the Gower's distance index on 19 bioclimatic variables [left], and index value of each cell with respect to the class to which it has been assigned [right]. Note the general pattern whereby the lowest distance values in each patch [light] tend to be located at its centre, while the highest [dark] values are located at the periphery. [Adapted from del Barrio et al., [2019]].

Numerical regionalisations are excellent material for assessing abiotic representativeness, but their production is strongly dependent on the availability of relevant geographical information. Where this is not possible, gradient analysis coupled with biota sampling can be used. In general, biological samplings also record abiotic data, which can be used to establish whether a certain protected territory harbours the environmental variation range preferred by the organisms to be conserved.

Figure 4 presents a very simplified example of gradient analysis, which makes it easier to identify the characteristic intervals of a certain predictor variable where the target species or community is found. This information can be derived directly from sampling, as in the case shown, or from more complex analyses, such as representing the species' occurrences in a multidimensional space. In this progression, we should bear in mind that the higher the predictive power of the method used [e.g. neural networks or decision trees] with respect to the species studied, the lower the ability to interpret the function of individual gradients.

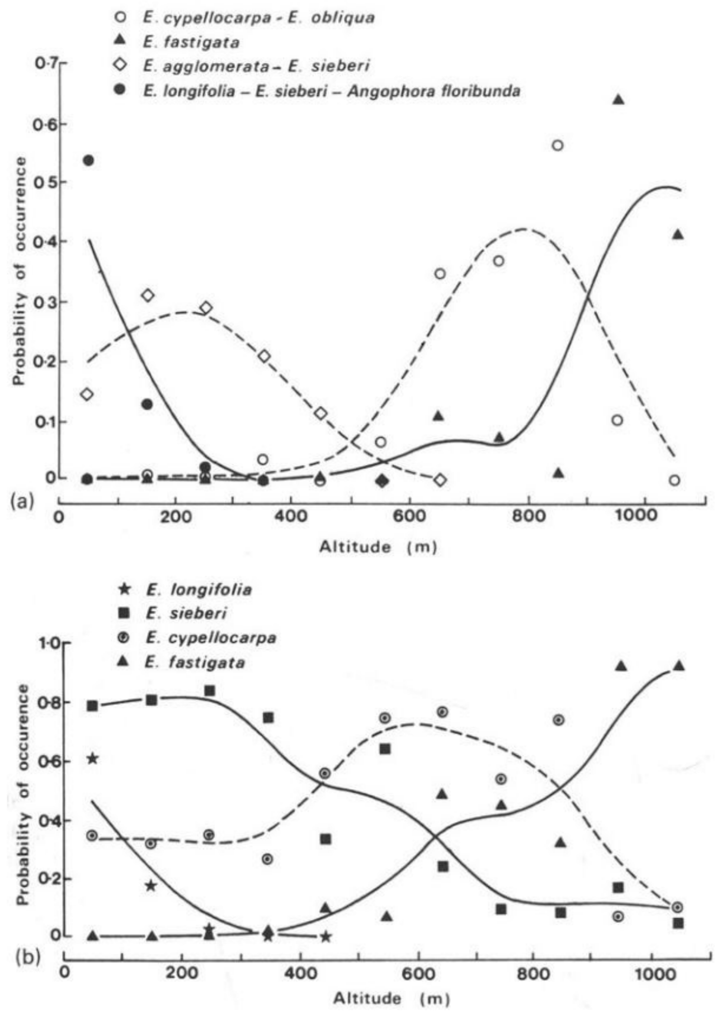


Figure 4. Distribution of Eucalyptus communities [a] and individual species [b] along an altitudinal gradient. Taken from Austin and Margules [1986].

3.1.2. Biotic representativeness

The representativeness of organisms and communities is usually measured in percentages of their distribution that are included in the network's reserves. This is a key point of the notion of coherence, as it channels rarity, endemicity, redundancy and even connectivity. The origin of the Natura 2000 Network illustrates this development very well.

The Natura 2000 Network was designed around the problem of adequately representing species [SpCIs] and habitats [HCIs] in a network of reserves [SACs]. With this approach, the European Topic Centre for Nature Conservation [ETC/NC] set criteria for drawing up preliminary lists of SCIs or candidate sites for becoming SACs [ETC/NC, 1997]. *These included hosting a sufficiently large and representative sample of each habitat type and species to allow for a favourable conservation status at EU and biogeographical region levels. In addition, a proportionate response should be given, so that a larger proportion of the resource within SACs is devoted to the rarer HCIs and SpCIs, while the more abundant ones have a smaller proportion of the resource within SACs.*

It is interesting to note that the problem of including the ranges of environmental variation of the landscapes to be conserved was implicitly assumed when considering the representation of HCIs. In fact, in the analysis of the representation of an HCI or SpCI within the SAC network, the ETC/NC established the requirement to reflect the variation of the habitat or species within the biogeographical region. In this respect, it is important to discuss briefly the inherent difficulties in carrying out an accurate mapping of habitat types that allows for a rigorous analysis of the representativeness component. The imprecise or ambiguous definition of many of the HCIs in the Interpretation Manual of European Union Habitats [European Commission, 2013] has created serious interpretation problems that have led many Member States to generate their own interpretation manuals. Rigorous mapping requires a precise definition that allows for identification in the territory and, most importantly, a delimitation [at an appropriate scale] that enables such a representativeness analysis. There is currently no common vision in this respect among the different Member States, which makes it difficult to obtain a homogeneous picture at the scale of a biogeographical region.

The ETC/NC proposed a procedure for the pre-selection of SCIs based, indicatively, on the distribution of HCIs or SpCIs considered necessary to be conserved [Table 1]. The representation thresholds applied were admittedly arbitrary. However, they reflected appropriately the need to protect fractions of the total HCI or SpCI distribution according to their nature. Thus, an HCI or SpCI is considered to be well represented in the Natura 2000 Network if all SCIs contain more than 60% of their distribution in the relevant biogeographical region, which should ensure a favourable conservation status. Reciprocally, if the representation in the Natura 2000 Network is less than 20%, the HCI or SpCI is considered a priority for additional monitoring.

Evaluación de la representatividad	Umbral de representación en la Red Natura 2000
Bien representado	> 60%
Requiere análisis detallados	< 20%
Requiere discusión caso por caso	20% – 60%

Table 1. Criteria suggested by the European Topic Centre for Nature Conservation [ETC/NC] to preliminarily establish the representativeness of the Natura 2000 Network with respect to HCI or SpCI. The percentages of representation refer to all SCIs in a biogeographical region. Adapted from ETC/NC [1997].

The representation criteria suggested by the ETC/NC were adapted by the various EU States to reflect their particular conditions. For example, in the case of Spain, it was considered appropriate to explicitly combine rarity and priority to establish representation thresholds [Table 2].

The use of habitats in the case of the Natura 2000 Network reflects the objective of conserving environments or landscapes, and is in line with identifying broad conservation objectives that lead to the preservation of whole ecosystems, beyond individual species that are perceived as important. This objective is more effective in protecting the common than the exceptional or rare aspects, and is generally applied in large spatial domains. For example, Dinerstein et al. [2017] assessed the percentage of land in each terrestrial biosphere ecoregion that was included in conservation reserves, against the overall target of all ecoregions having at least 50% of their territories protected.

RAREZA	PRIORITARIO	NO PRIORITARIO
Muy raro [< 33 % perc.]	100%	100%
Raro [33 – 66 % perc.]	80%	50%
No raro [> 66 % perc.]	50%	10%

Table 2. HCI or SpCI representation thresholds in the SCIs of the Natura 2000 Network applied by the Spanish State. Rarity levels are defined by the percentile corresponding to the size of the distribution within the biogeographical region. Adapted from Orella et al., [1998].

3.1.3. Representativeness in a changing world

The dynamism of biodiversity clashes with the static nature of protected areas, seriously hampering their ability to allow for the survival of biodiversity and the maintenance of the ecological processes for which they were declared.

The ability of static protected areas to conserve dynamic biodiversity is often questioned because, although they generally mitigate negative effects within their boundaries, they are extremely pressured at their borders, hindering the movement of species to other areas with suitable climatic conditions.

Climate change adaptation plans, based on current geographical patterns of biodiversity, may be insufficient to sustain future biota and natural processes due to the lack of knowledge of how biodiversity will respond to climate change.

Given that protected areas have spatially fixed boundaries and are often surrounded by a matrix of transformed land uses, the question arises as to how environmentally representative protected areas are when the climate is changing.

Rather than trying to estimate the effects of climate change on the species or habitats in a reserve, in this paper we propose an approach based on estimating the location of areas with similar environmental conditions to those of a focal protected area, both in the present and in the future. Assuming that the environmental conditions of a protected area are the main determinants of its conservation value [Albuquerque and Beier, 2015], representative environmental regions of each protected area can be located in present and future scenarios [Mingarro and Lobo, 2018]. This increases the likelihood of preserving the ecosystem functions and biodiversity represented by protected areas.

From a conservation point of view, the protection of current representative areas, sites with similar characteristics to the protected area, and future receptor areas, sites that in the future will have similar conditions to those currently hosted in the protected area, could facilitate the safeguarding of the environmental conditions under which each protected area was declared. However, this assumption has to be analysed: biodiversity is not evenly distributed across a climate space and, although climate is an important filter, other factors affect the distribution of biota, including biogeographical and evolutionary history, disturbance, geological and edaphic factors, dispersal constraints and biotic interactions. In order to overcome this challenge and prevent conservation strategies from relying solely on climate, an integration of abiotic variables as a subrogation for the biotic characteristics of the protected area is proposed herein. This knowledge can be used to anticipate and adapt protected areas to future changes.

Figure 5. Explanatory diagram for the estimation of climate and geodiversity representativeness, both for the present and for the future. By following this diagram it is possible to identify representative areas and receiving areas. N2K= Natura 2000 Network.

This representativeness estimation procedure can be divided into five phases [Figure 5]:

1. **Generation of variables. See Section 5.3. Abiotic variables.**

2. **Area of representativeness and variable selection**

The delimitation of the area of study is very significant as it is the basis on which representativeness will be considered. In the context of this guide, the area of study for estimating representativeness should be the biogeographical region. Furthermore, to implement this methodology in the Macaronesian region it makes sense to use the individual island as a spatial unit, as there is no spatial connection between islands. Depending on the purpose, it may be interesting to understand the climate of the entire Macaronesian region that a specific protected area represents [e.g. Figure 6].

Once the area of study has been identified, where representativeness will be estimated, the next step is to identify the most relevant variables

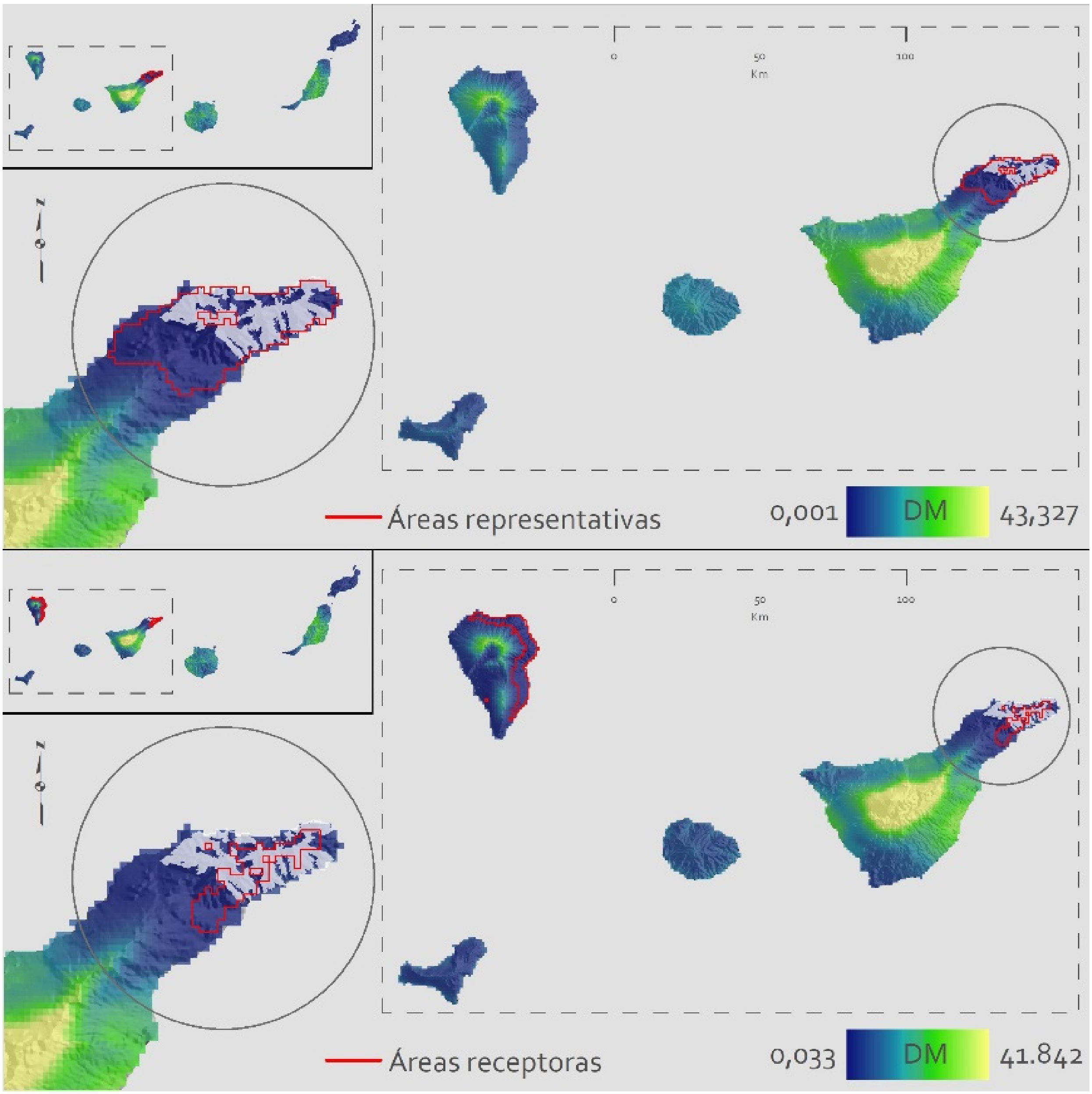


Figure 6. Climatic representativeness of the Anaga SAC [ES7020095], Canary Islands. The image above shows the representativeness, where a smaller Mahalanobis distance implies a higher climatic similarity. The representative areas [red line] show the distances included in the 90th percentile, within the protected area. The image below shows the receiving areas, areas that in the future [IPSL- SSP5] will have a similar climate to that currently found in this SAC.

for the analysis. In this case it is proposed to use a principal component analysis [PCA] to obtain the importance of each variable and to reduce the number of variables to be used. The PCA provides different uncorrelated factors, which account for a percentage of all variability. For each of these factors it is possible to select the original variable with the highest factor loadings, i.e. the primary variable best correlated with the values of each factor. There may be variables that are not represented by the factors obtained in the PCA, in which case it makes sense to introduce them into the analysis to increase variability. In addition, it is recommended to capture a high variability, above 80-90%, represented by the addition of the factors.

3. Representativeness analysis

The abiotic variables, previously selected, are used to calculate the Mahalanobis distance (MD) between the conditions of the protected area and the rest of the study area. For this purpose, the MD of each location to the climatic centroid of the protected area is obtained. In the case of climate data, the process is repeated for both present and future data. In order to obtain the future climate representativeness of a protected area, it will only be necessary to obtain the MD of the future climate space, using the current conditions in the protected area as a centroid and using the same variables selected for the present period. This provides a continuous measure, capable of representing not only sites with conditions equal to those of the protected area, but also sites with relatively similar conditions. The MD has been selected to measure climate similarity because this multidimensional measure takes into account the correlations of the variables and is scale invariant, regardless of the units used for each variable X.

4. Representativeness estimation

Following the previous steps, two continuous layers are obtained, one for climate and one for geodiversity, where low values indicate similarity and high values indicate dissimilarity of the representativeness of the protected area in question. In order to establish a threshold between what is representative and what is not, the 90th percentile (P90) of the MD values that appear in each representativeness layer within the protected area can be used. In the case of the future exercise, the P90 of the MDs obtained in the present climate within the protected area will have to be used. This makes it possible to demarcate areas with abiotic conditions that are highly similar to those of the protected area.

5. Abiotic representativeness

Once the climatic and geodiversity representativeness has been obtained, it is possible that these results overlap. This makes it possible to identify the places where the representativeness of both layers meet, giving an insight into abiotic representativeness. Similarly, if the intention is to estimate how abiotic representativeness will vary in the future, the geodiversity layer will remain unchanged, due to the assumption that geodiversity is not naturally altered over a period of decades, and only future climate layers will vary.

[CASE STUDY: Impact of climate change on the laurel forest of Tenerife]

Servicio de Biodiversidad, Dirección General de Lucha contra el Cambio Climático y Medio Ambiente, Gobierno de Canarias (Biodiversity Service, Directorate General for the Fight against Climate Change and Environment, Government of the Canary Islands)

The presence of laurel forest formations in the Macaronesian archipelagos is closely linked to certain ranges of climatic variables, such as the presence of mist, the precipitation and temperature, in such a way that changes in these variables over time can have a significant impact on the territorial representation of this relict formation.

The Government of the Canary Islands has carried out an internal analysis to assess the effect of climate change on the habitats of the "green mount" (monteverde) in Tenerife, made up of the natural habitats of Community interest '4050* Endemic Macaronesian heaths' and '9360* Macaronesian laurel forests (Laurus, Ocotea)'. The aim of the work was to assess how the climate scenario of these habitats has changed due to climate change and to determine how the range of these habitats 4050 and 9360 on the island has been affected, while generating a forecast of how these habitats will be affected in the future.

From a methodological point of view, existing climatic information was gathered for the main areas of current distribution of habitats 4050 and 9360 on the island (Teno, La Orotava, Anaga and Güímar) (Figure 7) for the periods 1970-1999 and 1993-2022 for comparison. Knowing the climatic requirements of habitat 9360 in Tenerife and using these raw data to model the temperature (T) and precipitation (P) of the ranges of both habitats, a climate space (T versus P) was constructed (Figure 8) where the climate distribution during these time frames was represented.

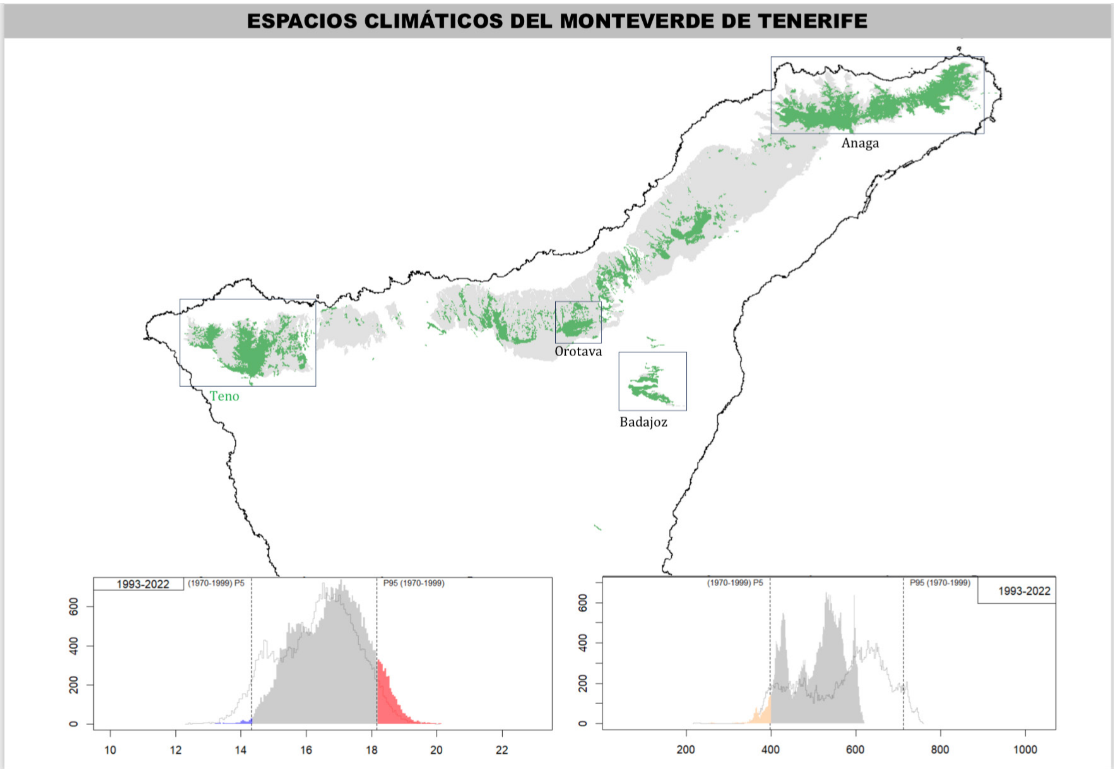


Figure 7. Above, potential [grey] and current [green] geographical distribution of habitats 4050 and 9360 in Tenerife. Below, distributions of mean annual temperature [left] and annual precipitation [right] for the periods [1970-1999, white] and [1993-2022, grey]. In blue [5th percentile] and red [95th percentile] overlap of both curves for temperature and in orange overlap of the 5th percentile for precipitation. There is no overlap for the 95th percentile of precipitation values.

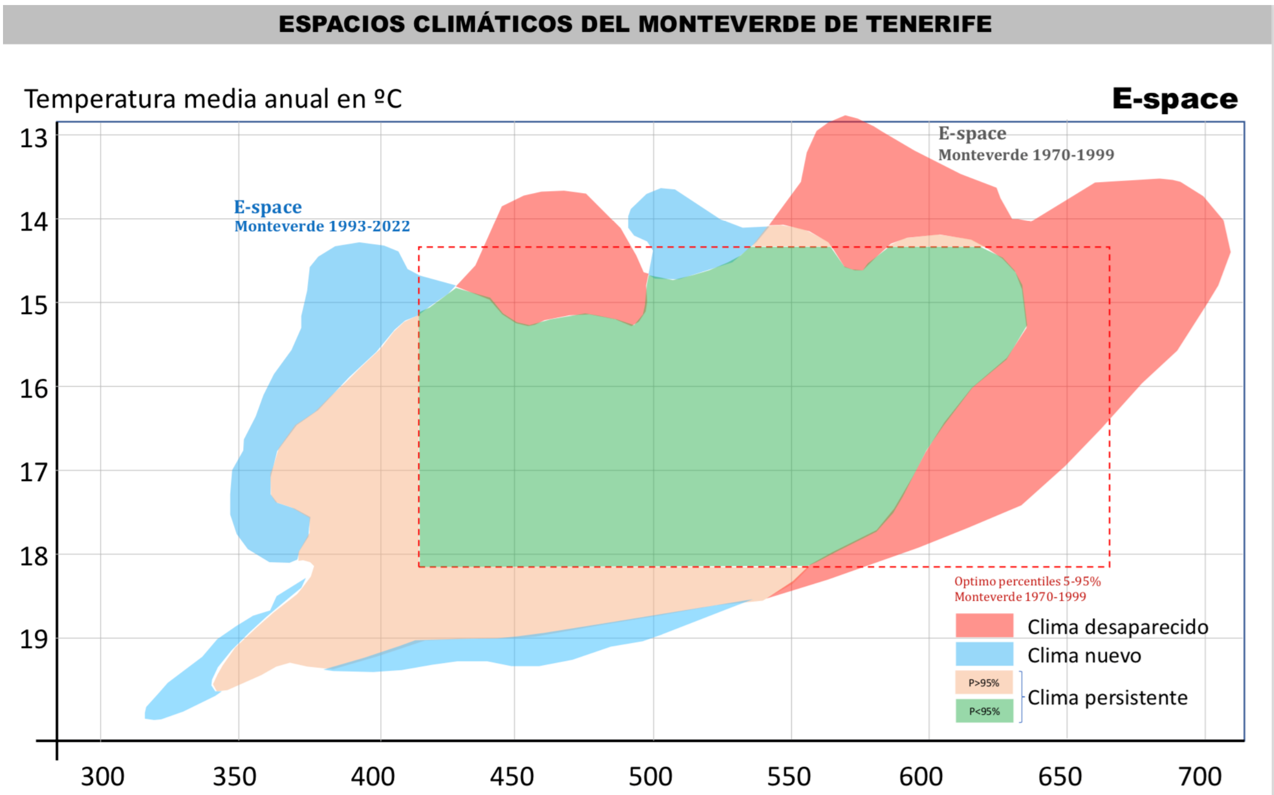


Figure 8. Extent occupied by habitats 4050 and 9360 in the Temperature-Precipitation climate space. In red, the 1970-1999 climate space that has disappeared, and in blue, the new climate space that emerged between 1993-2020. Green [P< 95%] and orange [P>95%] areas indicate persistence of climate space.

ESPACIOS CLIMÁTICOS DEL MONTEVERDE DE TENERIFE

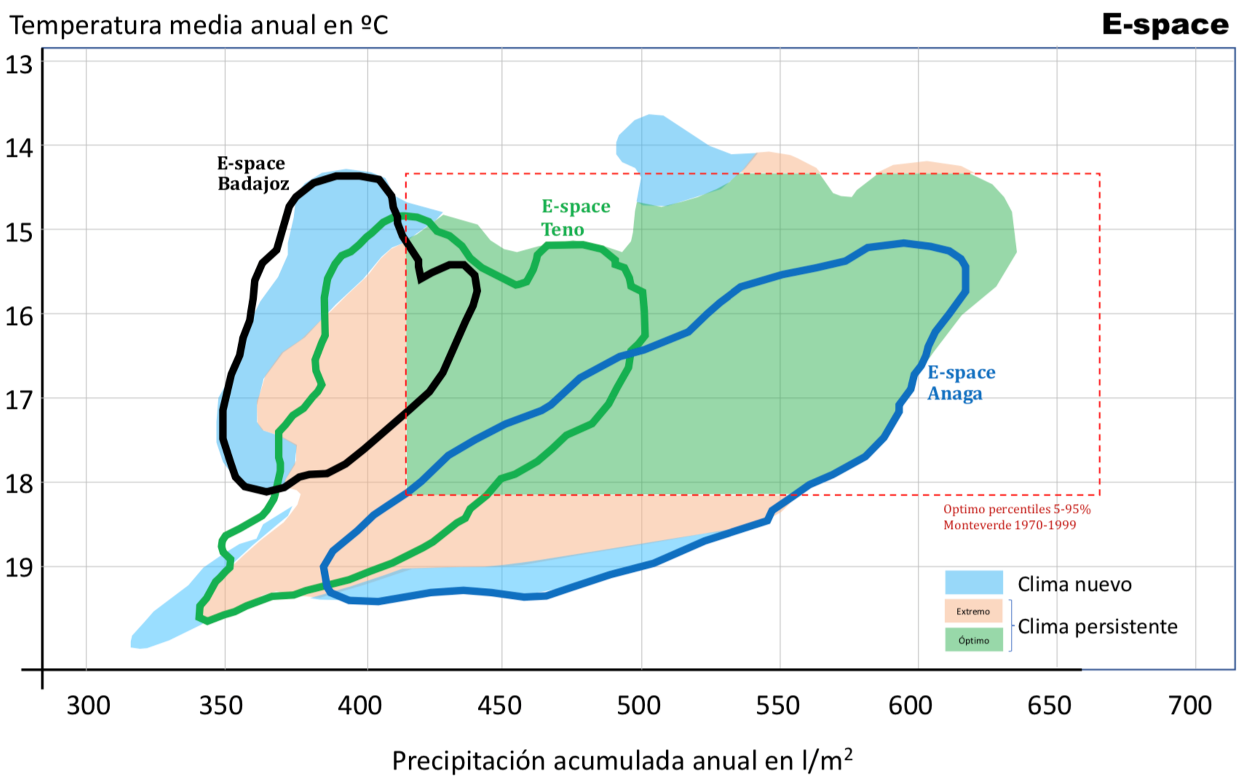


Figure 9. Distribution of habitats 4050 and 9360 of certain island regions [Teno -green line area-, Anaga -blue line area-, Teno and Badajoz [Güímar] -black line area-], in the global climate space.

As a result, the climate dominance from the period 1970-1992 in the analysed distribution of habitats 4050 and 9360 has shifted in the last 50 years towards warmer and drier conditions, in such a way that a significant fraction of their climatic space has disappeared ['missing climate' in red in Figure 8]. On the contrary, a new climate space has emerged ['new climate' in blue in Figure 8] and it will be necessary to observe its influence is on the survival of the habitat.

The progression towards a warmer and drier climate in the areas where these habitats currently spread may result in an altitudinal redistribution of both habitats towards the summit of the island, in order to follow their original climatic requirements. However, this altitudinal redistribution may be hindered by the inability of these habitats to follow climate change due to dispersal problems or by the lack of higher ground to colonise [as is the case in Anaga and Teno, whose summits are already occupied by these vegetation types] [Figure 9]. On the other hand, in the lower ranges of HCI 4050 and 9360 they may be replaced by the altitudinal redistribution of other ecosystems, such as thermophilous forests [as may occur in the area of Barranco de Badajoz, Valle de Güímar] or they may also incorporate new taxa that are highly competitive in the new climatic space.

In summary, there is certainty about the climate change that has occurred in the ranges of habitat 9360 towards warmer and drier conditions during the last half century, but uncertainty about the ability of this habitat to follow its climatic envelope, where this is still possible due to the existence of higher areas to colonise [La Orotava].

3.2. Rarity, endemicity and redundancy

3.2.1. Rarity

Representativeness is a method for conserving certain target entities, which in the case of the Natura 2000 Network are HCIs and SpCIs. The previous section advanced that the representation thresholds set for a given entity depend, among other things, on its distribution range. Thus, rare or restricted-range entities are favoured to have greater representation within the group of reserves. There are several reasons for this [Säterberg et al., 2019]. Rare species are not redundant with other species, by definition. Therefore, they contribute disproportionately, in relation to their extent and biomass, to the diversity of adaptations in a region, as well as to associated ecological functions and ecosystem services. Additionally, rare species have marked effects on the stability of their ecological community if disturbed. And finally, their low abundance and restricted range mean that the risk of extinction is always comparatively high for rare species.

The next logical step is to define rarity, which is usually linked to the extent of distribution of the habitat or species concerned. Globally, there is some consensus that a species is considered to have a wide range if it occupies more than 250,000 km^2, whereas if it occupies less than 1000 km^2 it is considered to have a restricted range. The thresholds for representation in conservation reserves for these types are, respectively, 10% and 100% [Rodrigues et al., 2004; Venter et al., 2014].

Since rarity is semantically a relative condition, a practical way to define rarity is to place the taxon or habitat in question among other taxa or habitats in a certain spatial domain. The Spanish adaptation of the ETC/NC criteria considers rarity as a function of the percentile that the size of an HCI's distribution occupies in all HCIs in the corresponding biogeographical region [Orella et al., 1998]. Thus, an HCI will be rare if the size of its range is between the 66% and 33% percentiles, and very rare if its distribution is smaller than 33% of all HCIs in the region. Consequently, rare or very rare HCIs should have up to 100% of their range included in the Natura 2000 Network [Table 2].

However, a species or habitat may be very common within a restricted area, or rare over a very large area. This is because rarity really depends on two attributes: geographical restriction and functional selectivity. In this connection, the scheme proposed by [Loiseau et al., 2020] can be used to qualify the rarity of HCIs or SpCIs included in a biogeographical region, and is developed below.

Geographical restriction refers to the extent of a taxon's distribution in a spatial domain. According to this, in the case of Natura 2000, an HCI or SpCI is rare if it occupies a small area in the biogeographical region being assessed. This can be quantified by an index Ri indicating the rarity of the entity i

$$R_i = 1 - \frac{K_i}{K_{tot}}$$

where K_i is the number of cells [e.g. UTM grid squares] where i is present, and K_{tot} is the total number of cells in the biogeographical region. The value of R_i varies between 0 for very common entities and 1 for entities with a very restricted range.

Functional selectivity refers to how particular the ecological niche of a certain taxon is regarding all other taxa in a spatial domain. This involves first selecting a set of adaptive traits or niche characteristics. In the case of animal SpCIs the trophic niche [Elton] can be used, and in the case of plant SpCIs or HCIs the environmental niche [Hutchinson] can be used, the latter possibly derived from a predictive distribution model [Section 3.3.1]. A ranking of all comparable taxa in the study region can then be made using this set of traits or characteristics. A Principal Coordinates Analysis [PCoA] is a good procedure for this purpose, as the resulting coordinates give quantitative support to the position of each taxon in the multidimensional space. Then, the average functional difference D_i of each taxon with respect to all other taxa can be measured by means of an index

$$D_i = \frac{\sum_{J=1, j \neq i}^{N} d_{ij}}{N - 1}$$

Where di is the distance between taxa i and j measured using Gower's distance index with the PCoA coordinates of those taxa, and N is the total number of taxa analysed. The value of Di varies between 0 when the taxon is very similar to all others, and 1 when it is very different.

Geographical restriction and functional selectivity are not necessarily correlated, and their intersections yield a more sensitive qualification on the spectrum from common to rare than when used separately [Fig. 10].

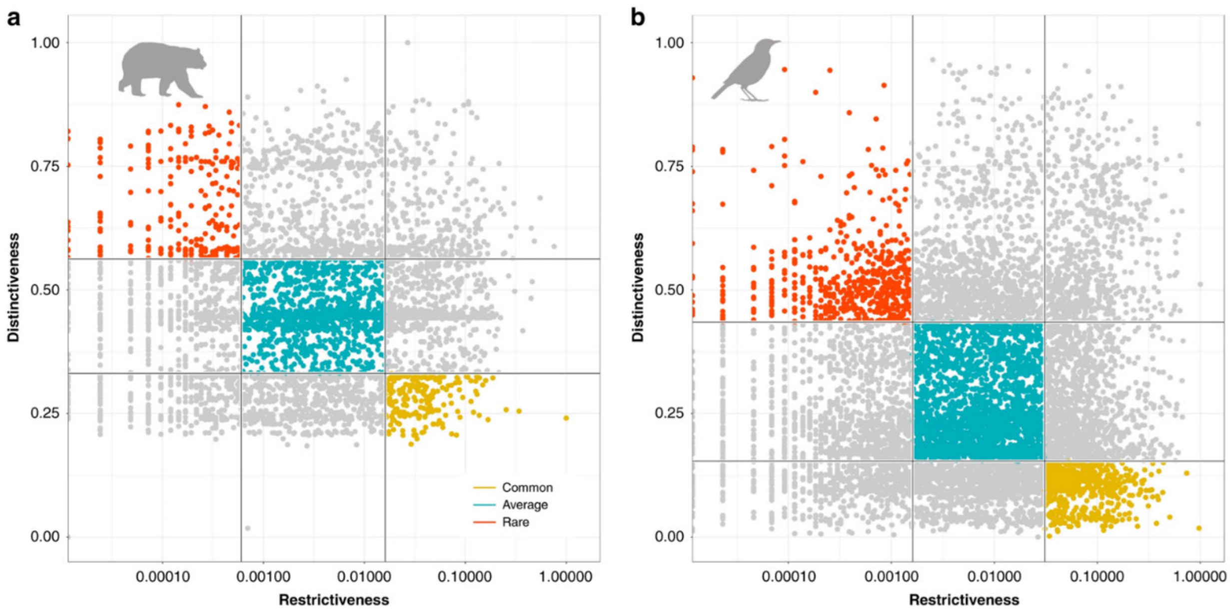


Figure 10. Ecologically rare species are defined by a combination of geographical restriction and functional selectivity. The graphs show these attributes for mammals and birds distributed around the world, using the trophic niche. Taken from Loiseau et al., [2020].

3.2.2. Endemicity

The problem of endemicity is very complex, especially in an island biogeographical region such as Macaronesia. The patterns obtained are strongly influenced by taxonomic treatment, spatial resolution and the extent of the area considered [Daru et al., 2020]. Detecting such patterns is not part of the purpose of this paper, and the problem is considerably simplified by recalling that, in the operational definition adopted for coherence, the requirement is that *all critical areas of rare, highly threatened and endemic species are included.*

3.2.3. Redundancy

In a broad sense, redundancy refers to the repetition of elements in a system, so that it is possible to maintain or reconstruct its function despite the loss of part of it.

This concept has been applied in conservation ecology to functional groups of organisms, i.e., groups of species that largely overlap their functional ecological niches. In this sense, redundancy favours ecosystem resilience, and functional groups with few representatives should attract greater conservation efforts [Walker, 1995]. Functional redundancy can be measured in a multidimensional way using variables that define the functional niche of species, although the evidence obtained is limited and should be handled with caution in predicting the effect of loss of individual species [Rosenfeld, 2002].

However, in the context of a coherent network of protected areas, redundancy refers rather to the over-representation of ecosystems to be conserved. This over-representation is a guarantee of the network's survival in the face of adverse events, which can range from local disasters to climate changes that substantially affect the domain of the conserved ecosystems. There is some similarity between this definition and the one described above, referring to species. However, the consideration of whole ecosystems explicitly introduces a spatial dimension.

Considering the problem globally, redundancy is proportional to the extent of the distribution of a certain ecosystem. IUCN therefore established threshold surface area conditions and values to determine the risk of loss of characteristic native biota due to restricted geographic distribution [Keith et al., 2013]. A subset of its Criterion B1 can be used to illustrate the approach. First, the extent of occurrence is defined as the smallest convex polygon that includes all occurrences of the ecosystem in question. IUCN then determines the risk as; Vulnerable if the polygon is less than 50,000 km^2; Endangered if it is less than 20,000 km^2; and Critically Endangered if it is less than 2,000 km^2.

The idea behind the IUCN risk criterion B1 is one of simple geographic concentration: the smaller the area where a certain ecosystem is present, the more exposed it is to significant local disturbance. This, together with the fact that IUCN is targeting this valuation method at ecosystems rather than species, marks a start on the way forward for integrating redundancy into the assessment of the coherence of the Natura 2000 Network.

It should be noted, however, that the IUCN approach is global, and that the criterion B1 described above refers to entire observed distributions of ecosystems. The case of the Natura 2000 Network poses its own challenges that need to be addressed:

- Firstly, the working scale of the Natura 2000 Network is continental. This means that even if a certain biota [an HCI or SpCI] extends beyond EU borders, its conservation issues will be assessed only within that territory. More precisely, the real scope of work is the intersection between the relevant biogeographical region and the political boundaries of the EU [e.g. the EU's Macaronesian Region excludes the African coast].

- Secondly, the heterogeneity of the territory comes to light when using a more detailed spatial scale, and methods such as the extent of occurrence mentioned above become less meaningful as the detail increases. In each case there will be an undefined, but always important, fraction of useless territory for the purpose of preserving the presence of some biota within the convex polygon enclosing its continental range. That fact cannot be overlooked. An extreme case is that of an archipelagic biogeographical region such as Macaronesia, where the extent of occurrence of any terrestrial HCI, present in all archipelagos, would include huge areas of ocean. This is still useful for the purposes of Criterion B1, but is of little use in assessing the redundancy of the Natura 2000 Network.

- In addition, it can be argued that conservation issues should be assessed exclusively for Natura 2000 sites, in order to ensure the self-sufficiency of the network to conserve its objectives. This increases the need for texture in any methodological approach.

Establishing redundancy based on gross areas of observed distribution of an HCI involves following the 'more is better' criterion. If successful, the result ensures the preservation of the maximum possible assets of the HCI in question, and can therefore be considered prudential. However, there are two problems with this approach. Firstly, it is not known whether the conserved area is sufficient. Secondly, it is likely that the maximum area conserved cannot be achieved, due to the multiple interactions that occur when designating protected areas in environments subject to multiple exploitation, as is the case in Europe. Naturally, the second problem exacerbates the first.

One can go back to the definition of redundancy given initially, as over-representation. Over-representation with respect to what? With respect to the smallest area that can contain a stable and persistent sample of the HCI to be conserved. That is, in terms of the Natura 2000 Network, the Favourable Reference Area (FRA).

The FRA is defined as the total area of a habitat type in a given biogeographical region or marine region at national level that is considered the minimum necessary to ensure the long-term viability of the habitat type and its species, and all its significant ecological variations in its natural range, which is composed of the area of the habitat type and, if that area is not sufficient, the area necessary for its restoration (European Commission, 2022).

The FRA is thus presented as a relevant variable for estimating redundancy. The problem is that the definition given tends to be interpreted as a historical, probably pre-industrial, occupation of most HCIs, when human population densities and land use were substantially lower. In this regard, it was recommended that FRAs should be at least the area that had the relevant HCI when the Habitats Directive came into force (Evans and Arvela, 2011). This requirement has significant theoretical and practical issues, including: the lack of operational baselines to establish the original range of most HCIs; the arbitrary setting of 1992 as a time reference; and the absence of functional criteria to support any resulting values. Therefore, a relatively recent survey showed that most member states have developed their own applications (Bijlsma et al., 2018).

The FRA used to estimate the redundancy of the Natura 2000 Network must: effectively refer to a minimum area, rather than to a potential maximum or historical value; have a clear functional significance; be interpretable regardless of the historical point in time at which it is obtained; and be derived using a general method that can be applied to multiple HCIs without major variations.

The ratio of number of species to area meets all the above requirements. Its origin is the theory of island biogeography of MacArthur and Wilson, (1967). It predicts an increase in the number of species as the surveyed area increases, due to the likelihood that larger areas will include greater environmental diversity and thus new ecological niches. However, the number of species becomes progressively saturated; therefore, when large area values are reached, the occurrence of new species is considerably reduced.

This relationship is expressed by a power ratio:

$$S = c \cdot A^{z}$$

where S is the number of species, c is a constant, A is the area under consideration and z is an exponent that varies characteristically according to the environment or biota studied. The function is easy to parameterise empirically using pairs of values (a, s) to fit its linear transformation:

$$\log S = \log c + z \cdot \log A$$

Such pairs of values can be obtained for each HCI by field sampling.

Saturation in a power function is not asymptotic, but can be handled, nonetheless. Thus, the FRA would be the smallest area containing a significant percentage of all species found for the HCI in question (e.g. 95%), which can be determined analytically on the adjusted function. The logic is that, if there is a high spontaneous proportion of all available species, the area preserves most of the ecological niches and trophic functions of the original ecosystem, and can therefore be considered as a stable sample in the medium term.

The approach of relating number of species and area has been selected by the Spanish State to establish favourable reference values for HCIs [Camacho, 2024].

Once the FRA has been obtained, the definition of redundancy as over-representation can be taken up again. If R is the extent of a certain HCI represented in the Natura 2000 Network, redundancy p can be expressed as

$$p = \frac{R}{AFR}$$

All the steps described up to this point should be carefully evaluated by experts in the HCI in question. Particularly, the analytical determination of FRA as an area supporting a certain proportion of species only provides a neutral result, which, however, can be a useful starting point for an expert to help establish the final FRA. On the other hand, an explicit decision needs to be made as to whether the representation of a certain HCI in the Natura 2000 Network should be worked out as a whole for the entire biogeographical region concerned, or whether it would be more prudent to do so separately for each geographical variation that is identified as relevant.

3.3. Connectivity

Regional connectivity is an expression of the ability of a given taxon to transit a territory, to the extent that it facilitates or impedes its dispersal [Taylor et al., 1993]. It is the result of the spatial organisation of habitats and the characteristics of the ecological niche of the taxon under consideration. Although parameterised on a taxon-specific basis, it is an extrinsic spatial property of the landscape that reflects the structure of the dispersal process and can be calculated in the absence of the dispersal process. As it depends on the dispersal capacity of the taxon under study, the scale at which regional connectivity is estimated is given by the scale of dispersal of the taxon.

This transit occurs along a gradient of suitability that the territory as a whole offers to the species and not by a categorisation of the territory into favourable or unfavourable areas for the taxon. The transit of species depends on relative differences in suitability along this gradient and not on the absolute suitability of a particular location. For this reason, connectivity can only be parameterised in heterogeneous territories with different suitability values for the taxon in question. Dispersal is, in turn, conditioned by the spatial configuration of the taxon's populations, which will act as the beginning and end of such movements.

3.3.1. Connectivity models based on cost surfaces

There are various methods for modelling connectivity, such as dispersal models or models based on cost surfaces. The former are based on the simulation of the movement of species, based on their survival and dispersal capacity, from an existing population that creates individuals and the distribution of these individuals throughout the territory [Pearson et al., 2004]. Models based on cost surfaces express regional connectivity in terms of the cost of moving across a territory. While dispersal models have a more dynamic and temporal character, dispersal models focus on the structure of the landscape and do not include a temporal dimension, and can therefore be used in the absence of the dispersal process. These features make them more practical for obtaining a structural view of connectivity.

To explain the concepts associated with connectivity, and as an example of a modelling methodology, the project "Technical assistance for the assessment of ecological connectivity of habitat types in Spain and identification of an integrated network of corridors", funded by Tragsatec [ref. TEC0005797] and completed in October 2023, will be used here. It used the concept of regional connectivity to model the ecological connectivity of 31 forest HCIs, using connectivity models based on cost areas. The models were generated using the regional connectivity algorithm ALCOR [del Barrio et al., 2006; Rodriguez Gonzalez et al., 2008], which works as an extension of the IDRISI program and uses GIS raster images.

Cost is defined as the cumulative friction when transit occurs. Friction, or resistance to movement, informs on the difficulty of movement that a territory offers to a species. In other words, it is opposed to its suitability.

To obtain movement cost values, it is then necessary to encode the area of study into a surface of friction values. In the methodology used for the above project, this coding was carried out on the basis of predictive distribution models [Figure 11.2], based on the ecological niche of the taxon and bioclimatic data of the study area.

Based on the concept of ecological niche, predictive distribution models explain the distribution of a species based on its response to a set of environmental predictors [Guisan et al., 2017]. In the aforementioned project, the models were generated using the Random Forests algorithm [Breiman, 2001].

Predictive distribution models report the probability of occurrence of a species in an area by giving values between 1 [occurrence] or 0 [absence] and can be understood as suitability surface areas. From this probability, the friction surface [Figure 11.3] can be obtained as the inverse [1/p] or the complement [1-p] of the calculated probability.

As the cost is the cumulative friction during the movement between points of the territory, in order to obtain its values, it is necessary to know the configuration of the populations between which this movement is going to take place. To do this, it is necessary to apply a discriminating criterion to the observed distribution [Figure 11.1] in order to define the populations, which, in the methodology applied, consisted of setting a threshold dispersal distance. This distance should reflect the dispersal ability of the species to be modelled and allows two populations to be distinguished as different from each other. Thus, two pixels will be considered as belonging to two different populations if they exceed this threshold dispersal distance.

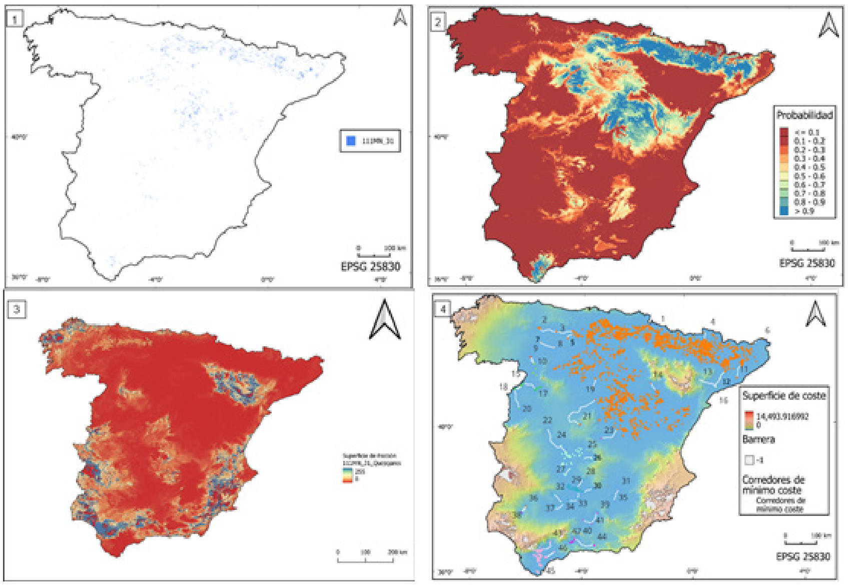
Once the population configuration and friction surface have been obtained, the reference cost surface can be generated, which shows the cost of movement from each point in the area of study to the nearest population. The cost will show minimum values in areas where populations are present, and maximum values where they are absent. If interpreted as a topographical map, lower cost areas will form valleys and higher cost areas will form peaks. Continuous areas of relatively low cost will act as green corridors, while areas with high cost values can be considered barriers. During this same process, the least cost corridors between populations are calculated by looking for the lowest cumulative friction [lowest cost] from the locations where the suppressed population is located to the nearest population.

Therefore, these connectivity models based on cost surfaces are composed of [Figure 11.4]: a cost surface, a set of populations, and a set of least-cost corridors connecting the populations.

A particularity of the methodology developed for the project was to represent the resulting connectivity models as network graphs.

The graphs are a simplification of the connectivity network in which the populations are the nodes and the corridors are the edges [Figure 11.5]. The corridors only connect to the nearest population and not to several populations, so only one corridor leaves each population. The network thus formed is called "directed", as its edges express the direction of the connections between vertices.

The use of these graphs allows the abstraction of the spatial dimension and the analysis of the network structure in terms of connectivity rather than geographical organisation. By disregarding these spatial constraints, the relationships between populations are more evident and the analysis of interactions within the system is facilitated, allowing the identification of holistic properties that would not otherwise be evident from direct observations. In line with the above, certain attributes, including the size, modularity or connectivity of the network can be measured and compared with those of other connectivity scenarios for the same habitat, or with the networks of other habitats for the same scenario.



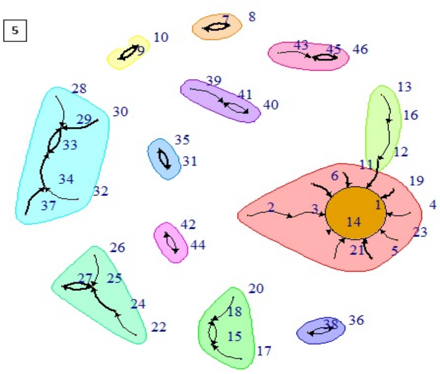


Figure 11: Maps of 1] observed distribution, 2] predicted distribution, 3] friction surface area, 4] connectivity and 5] network graph, for the habitat 111MN_31_Quercus faginea, Q. humilis, Q. canariensis woods and those of their hybrids. 1] Observed occurrences are shown in blue. 2] The colour palette indicates the probability of occurrence according to the values indicated in the legend. 3] The colour palette indicates the variations of the friction value [0-255] as indicated in the legend. 4] The map consists of the cost surface area, transit barriers [values of -1], least cost corridors and numbered populations. 5] Network graph with the structural organisation of populations, least cost corridors and clusters. The width of the corridors is proportional to the cost, being smaller the greater the thickness, and their directionality is given by the arrow. The thickness of the nodes is proportional to the size of the populations.

3.3.2. Methodology

Below are the steps for the generation of connectivity models based on cost surfaces [Figure 12], extracted from the methodology applied in the project "Technical assistance for the assessment of ecological connectivity of habitat types in Spain and identification of an integrated network of corridors" [ref. TEC0005797].

1. **Generation of predictive distribution models.** Predictive distribution models were generated using the Random Forest algorithm [Breiman, 2001], from observed distributions and selected bioclimatic predictors, and were validated using the OOB [*Out of the Bag*] error and the AUC [*Area Under the Curve*] measure. The observed distributions of the 31 forest types

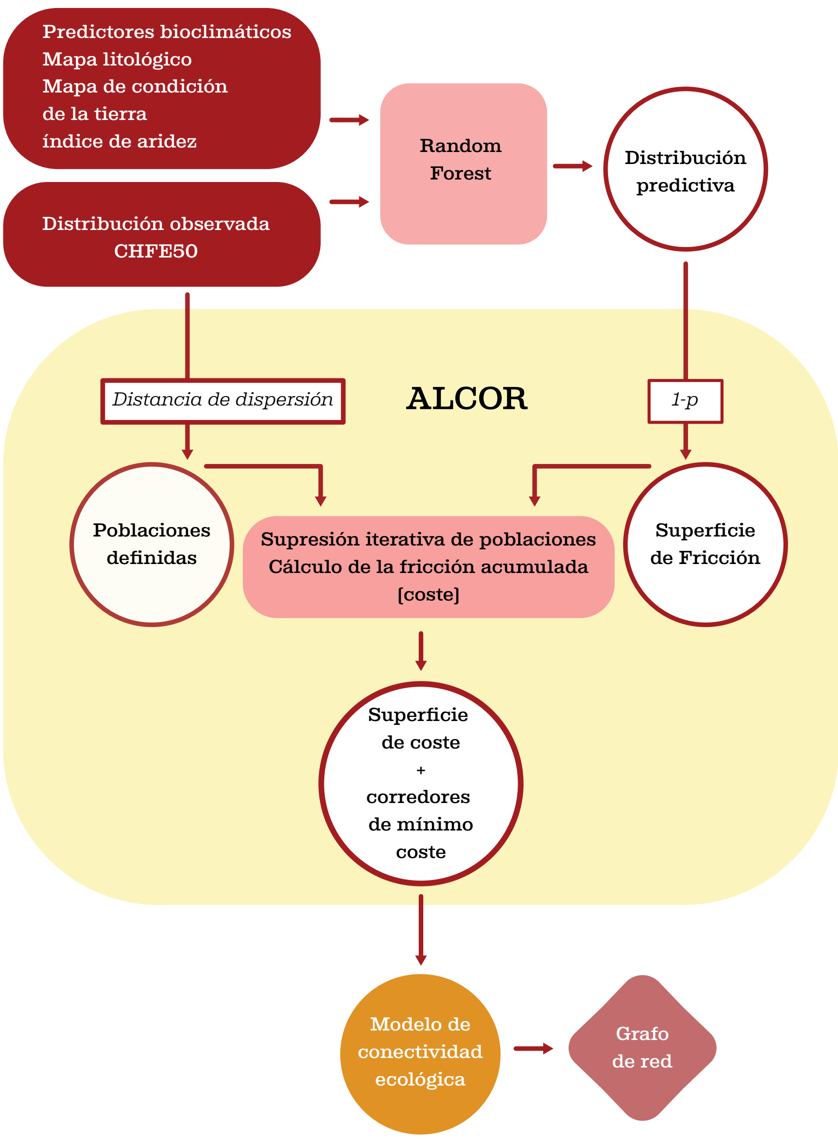


Figure 12. Flowchart with the methodology developed for the project "Technical assistance for the assessment of ecological connectivity of habitat types in Spain and identification of an integrated network of corridors".

were obtained from the CHFE50 geospatial database [Sánchez de Dios et al., 2019], which contains the geographical distributions of the main native forest and shrubland types in Spain, at a scale of 1:50,000. Climate, lithological and maturity stage data were used as predictors. Climate predictors are described in ANUCLIM [Xu and Hutchinson, 2016], a package containing climate variables. In this case, a climate file developed for Iberia [A. Ruiz et al., 2011] was used and values of the variables were obtained for the period 1981-2010. The lithological map of Spain by Riba and Vilar, [1969] was included and, to reflect the climatic particularities of Spain, the FAO-UNEP aridity index [Middleton and Thomas, 1992] was included. The index was calculated using the R r2dRUE package [A. Ruiz *et al.*, 2011]. The land condition map of Spain for the period 2000-2010 [Sanjuán *et al.*, 2014], which attributes a maturity value within a range between degradation and reference vegetation, was also used.

2. **Production of the connectivity model.** Introducing the predictive distribution models and the observed distributions in ALCOR, we obtain the cost surfaces, observed population configuration and minimum cost corridors, which make up the connectivity model.

   ALCOR transforms the predictive distribution into a friction surface area [1/p] and, by means of a previously established dispersal distance, defines the populations from the observed distributions. The cost surface area is generated through iterative suppression of the populations and calculation of the cost associated with them. In the same process, the least cost corridors between each population and the nearest population are calculated. Files are generated with the cost associated with each corridor..

3. **Network graphs.** The transformation of the connectivity models into network graphs is done using the igraph package [Csardi and Nepusz, 2006]. The populations will be the nodes of the network and the corridors, the edges. These networks will be directed, as corridors indicate the direction, and can also report the cost of each corridor, using the cost files generated in the previous step. By using igraph, different graph parameters can be obtained and explored**.**

3.3.3. Application to the Natura 2000 Network

The project "Technical assistance for the assessment of ecological connectivity of habitat types in Spain and identification of an integrated network of corridors" did not aim to assess the contribution of the Natura 2000 Network to the connectivity of the habitats modelled, so the occurrence data were used regardless of whether they were included in the network.

In order to apply the methodology described above to the Natura 2000 Network, it would be necessary to add as additional attributes to the populations, their inclusion in the network. Thus, the definition of the populations that make up the connectivity network is carried out following the process already described, but they result in populations identified according to the SCIs or SACs that contain them. The nodes of the resulting network graphs are then identified with these spaces [Figure 13].

Adding the attributes of inclusion in the network spaces as attributes allows for the integration of the connectivity networks generated for the different habitats into the same network. Connectivity models are habitat-specific and, as in the case of project ref. TEC0005797, are not comparable with each other as they only reflect the relationships between the habitat populations for which they have been generated. By incorporating inclusion in the Natura 2000 Network, these models already have common elements that will enable their integration: the sites to which the populations belong. Thus, the integration of the different connectivity models results in a network that reflects properties of the Natura 2000 Network itself

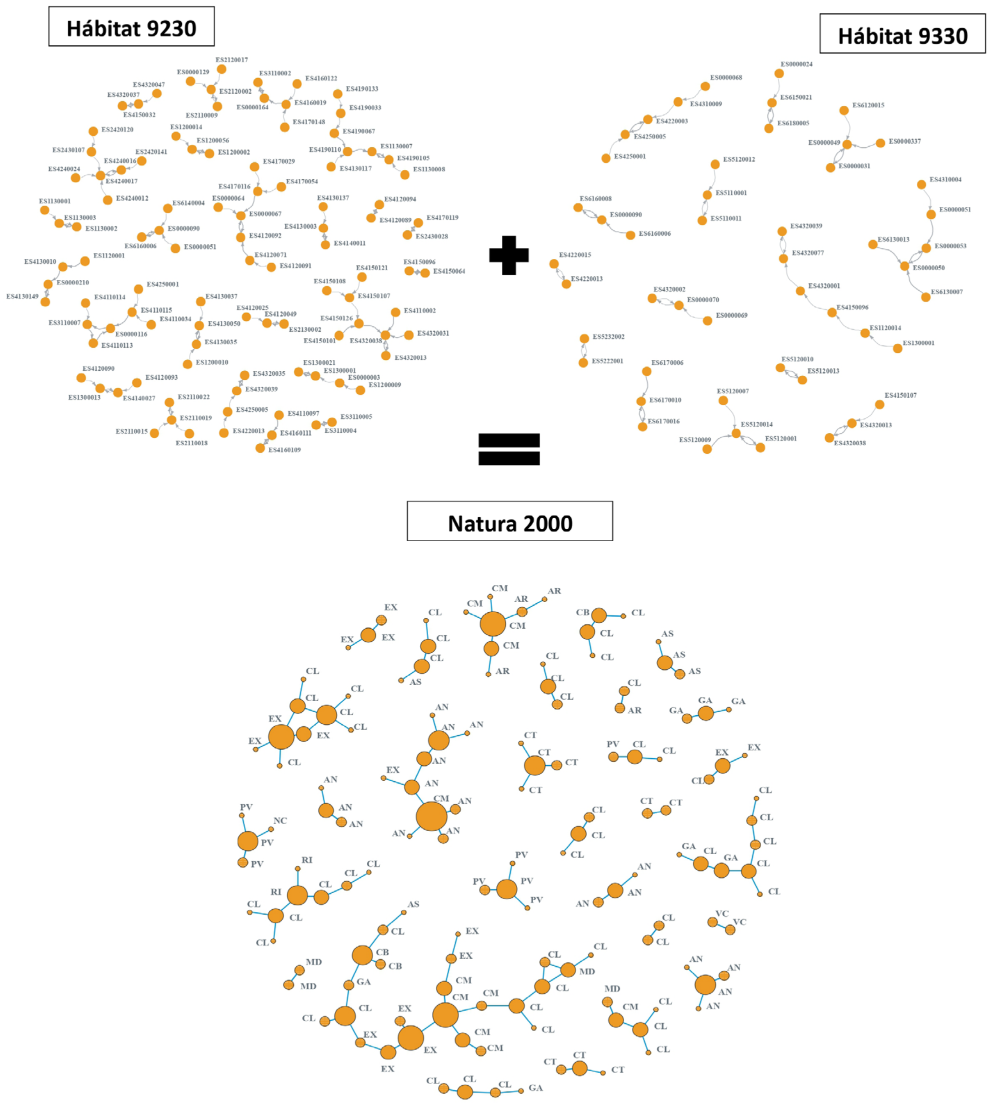


Figure 13. Network resulting from the integration of the network networks for HCIs 9230 Quercus pirenaica and 9330 Q. suber, carried out in an exploratory exercise. In the individual networks, the nodes are identified with the codes of the SCIs containing the populations. In the integrated network, the nodes are labelled with the code of the Autonomous Communities to which the SCIs belong in order to facilitate the interpretation of the image.

The resulting network will be more complex than the individual networks that make it up. Those SCIs or SACs that are common to more than one network will be unified in the integrated network, while those that only form part of one network will be added directly to the final network. All connections from the individual incoming nets are transferred to the outgoing nets. In cases where a node, i.e. SCI or SAC, is a source in one network and a destination in another; this node will act as a vertex linking two sub-networks within the final integrated network.

Having obtained an integrated network for Natura 2000 sites, the connectivity structure of the network can be characterised and its effectiveness in securing conservation objectives can be assessed. Parameters such as network size, which indicates the number of corridors in the network; density, which reports the proportion of connections observed; or modularity, which assesses how significant the clusters formed within the network are, are some of the network characteristics that can be obtained for analysis. The exploration of the characteristics of the integrated network will make it possible to detect the contribution of Natura 2000 sites to the connectivity of the resulting network, how resilient the network is, or what degree of connectivity would be most desirable for its conservation.

3.4. Resilience

3.4.1. Definition of resilience

Resilience is the resistance of the system to disturbances or damage caused by natural and anthropogenic factors. A resilient network has the ability to absorb such damage and reorganise itself to retain (or return to) the same function, structure, and ecological identity.

Disturbances can be measured at ecosystem or habitat level. In the latter case, the habitat is species-specific. However, resilience is difficult to measure, as disturbances may affect each ecosystem, habitat, or species differently. There is no standard methodology for measuring resilience that is easy and effective to apply.

Biodiversity monitoring methodologies can be used, which usually require field data, either by remote techniques (photo-trapping cameras, automatic sound recorders, etc.) or directly through field work. However, these methods end up being expensive, time-consuming for data collection and analysis, and can only be applied to small study areas. In addition to this, if biodiversity is used as an indicator, by definition one has to wait for it to change before making a decision. In other words, at least one species needs to become extinct. Only after the extinction of a species has been ascertained can the use of biodiversity to measure resilience after a disturbance be verified. Obviously, this method is very slow, difficult to implement, and therefore impracticable

An alternative is the use of data from remote sensing, the science of studying the surface of planets remotely by analysing the energy reflected from the planet's surface. This energy can be reflected sunlight (passive sensors), or a beam of energy emitted by the satellite itself (active sensors). Remote sensing provides data continuously over time, over the entire surface of the planet. There are satellites with high temporal periodicity (MODIS, 2 images per day) and low spatial resolution (250 m to 1 km), and low/medium temporal periodicity (Landsat, 1 image every 16 days; Sentinel, one image every 5 days) and high spatial resolution (10 m to 60 m). Thanks to the quality and continuity of remotely sensed data, a standard methodology can be established that allows us to indirectly analyse how resilient a habitat is.

3.4.2. Method for calculating resilience

In this paper, we propose to use the method developed by Arenas-Castro and Sillero (2021). This method monitors changes in habitat suitability in species through the calculation of ecological niche models with time series of satellite imagery products. This method assumes that species are more vulnerable when they experience greater fluctuation in habitat quality: that is, the greater the changes in habitat, the greater the pressure on the species. In other words, a species will have a poorer conservation status when human disturbance leads to a reduction in habitat quality. Therefore, a species will be more resilient when the quality of the habitat where it is found remains constant or increases over time, or when it manages to recover after suffering a reduction in habitat quality. Thus, it is possible to analyse the resilience of habitats for a particular species, or for several species together (see below). The method was successfully tested at different spatial scales: at 10 km in the Iberian Peninsula and at 50 km in Europe. The MontObEO project (https://montobeo.wordpress.com/) is developing a Google Earth Engine (GEE) application that implements the method by Arenas-Castro and Sillero (2021) in the Montesinho Natural Park in northwest Portugal.

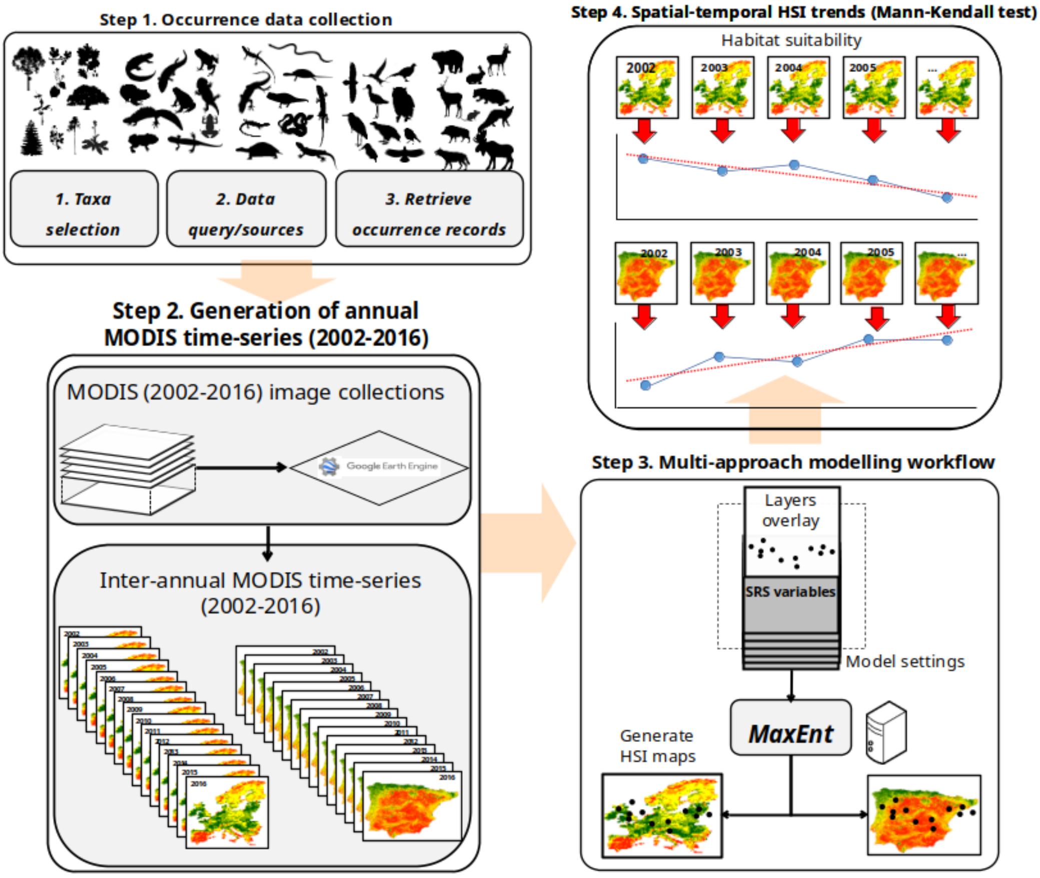


Figure 14. Description of the process of estimating resilience for a priority species or habitat. The process is divided into four steps: 1] obtaining species or habitat distribution data; 2] obtaining time series of remotely sensed variables from sensors such as MODIS or satellites such as Landsat or Sentinel with a given periodicity [annual, although it could be weekly or monthly, for example]; 3] calculation of ecological niche models over time [based on the selected periodicity] with the Maxent algorithm; and 4] estimation of trends over time with the Mann-Kendall test [positive, negative or null trends]. This methodology can be applied to a single species or habitat, or to groups of species or habitats, over any extent, time period, and periodicity, provided that satellite data are available.

In brief, the methodology consists of the following steps:

1. **Collection of species distribution data:** Four taxonomic groups were considered: vascular flora, amphibians, reptiles, birds, and mammals. The occurrence data for each species were obtained from different online repositories, including national and continental atlases [from Portugal, Spain, and Europe], the Global Biodiversity Information Facility [GBIF; https://www.gbif.org/], https://www.gbif.org/], databases with inventories, and flora and fauna collections. Species distribution data will be linked to environmental variables obtained from satellites [step 2] with a modelling algorithm [Maxent; step 3]. As no time series of species distribution data are available, the same distribution of each species was modelled over time. Only distribution data from the same period as the environmental variables [2002-2016] were considered. The distribution data were curated to remove errors in coordinates and specific names, as well as removing duplicates and clusters of points resulting from sampling biases.

2. **Processamento e integração de dados ambientais:** The environmental variables were obtained from the MODIS sensor and represent the main dimensions of ecosystem functioning and dynamics, such as carbon cycle dynamics, heat dynamics and radioactive balance. Six variables were included in the models: land surface temperature, which is an indicator of heat dynamics; evapotranspiration, which indi-

cates vegetation cover properties; enhanced vegetation index [EVI], an indicator of vegetation status and productivity; surface reflectance, an indicator of land surface change; annual area burned and time since fire, both of which are indicators of human disturbance. The variables were computed between 2001 and 2016 on an annual basis.

Variables were obtained from Google Earth Engine [GEE] [Gorelick et al., 2017]. GEE is a cloud platform that enables the analysis of large geospatial datasets in a scalable and effective manner. Developed by Google, GEE provides access to a wide range of earth observation data, including satellite imagery, climate data, topographic information and more. It includes all public Earth Observation programmes [Landsat, Sentinel, MODIS]. GEE provides tools and algorithms for processing and analysing geospatial data on a global scale. This includes capabilities for time series analysis, image classification, change detection, and land process modelling. It also allows for species distribution modelling with algorithms such as Maxent [Campos et al., 2023] or Random Forest [Crego et al., 2022]. GEE uses JavaScript as its main programming language to write scripts and run geospatial analysis. Users can take advantage of specific GEE function libraries to access data, perform spatial operations and perform advanced analysis. GEE is designed to handle large data volumes quickly and efficiently, leveraging the Google Cloud Platform infrastructure. This allows complex analyses to be performed on global-scale datasets in a matter of minutes or hours. Google Earth Engine is available free of charge to academics, scientists, developers and non-profit organisations.

3. **Ecological Niche Modelling:** The models predict habitat suitability for each species, following standard processes [Sillero et al., 2021; Sillero and Barbosa, 2021]. In the absence of time series of distribution data, the same species ranges are modelled over time with the time series of MODIS products. The distribution data are restricted to the years of the MODIS products [or any other sensor used]. The study used the Maxent algorithm [Phillips et al., 2006, 2017] to model species from five taxonomic groups: vascular plants, amphibians, reptiles, birds, and mammals. All parameters entered in Maxent [30% test data, 10 replicates, cloglog output format] were always the same for each model. The Maxent models were computed in R, although they can now be run in GEE [Campos et al., 2023]. Maxent is beneficial to be used in this context because it only requires occurrences and background [a random sample of the conditions available in the study area] as species distribution data [Guillera-Arroita et al., 2014; Sillero and Barbosa, 2021].

4. **Análise de tendências:** The Mann-Kendall test, a non-parametric statistical test that assesses monotonic trends in time series data, is applied on the time series of ecological niche models. The Mann-Kendall test was run in R, with the SpatialEco package, although it is also implemented in GEE.

This method can be applied to any area of study, regardless of its size, and at any spatial and temporal resolution, provided that satellite and species distribution data are available. The method provides information on changes in habitat quality over time [whether quality is increasing, decreasing, or remaining constant] at the pixel level. In addition, trends can be obtained for a particular species, or a set of species [taxonomic or functional group], simply by calculating the average of the slopes [S] of the trends. Thus, it is possible to know whether habitat quality has declined, for example, for all the birds analysed in the study area. Putting the trends for all species together gives an overall map of changes in habitat quality across the territory. This method can easily be implemented in a GEE application, which is a website that runs a GEE script independently of the Google platform. That is, the user gets to run a series of analyses in GEE without accessing the main platform and without needing to have an account on the main platform. In this way, the user can visualise trends in habitat quality for a number of species in a given study area.

In the case of Macaronesia, it would be necessary to collect data on the species to be modelled with an error in the coordinates in accordance with the desired spatial resolution. This in turn implies that environmental variables are available at that spatial resolution. MODIS provides variables at 1 km, so the error in the coordinates of species occurrences should be less than 500 m. If the models had to be calculated at a higher spatial resolution (100 m, for example), the most suitable sensors would be Landsat and Sentinel, although the number of environmental variables available would be much smaller and basically focused on landscape dynamics. In the case of MODIS, the temporal resolution is 2 images per day (one daytime, one nighttime); Landsat has one image every 16 days and Sentinel has one image every 5 days. However, the number of images available over time may be significantly reduced, depending on the presence of clouds in the images. Therefore, depending on the sensor selected and the available imagery, the periodicity of the trends could be weekly, bi-weekly, monthly, or yearly. The computation time for all analyses depends on the number of species and variables included, the time interval, the periodicity, the spatial resolution, and the extent of the study area. If all analytical processes are performed in R, the computing time required can be extremely long (up to several months). In GEE, the computation can take a few minutes per species. Unfortunately, GEE does not have an automatic data download process in place, so it may take a few hours to get the results.

[CASE STUDY: Naturalness in the Canary Islands and habitat monitoring]

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Detecting changes in habitats, based on reference patterns, makes it possible to identify trends over time in the conservation status of these habitats, which contributes to decision-making in land management.

The Government of the Canary Islands is promoting two projects whose objective is, on the one hand, to provide information on the state of naturalness of the Canary Islands (understood as a gradient of anthropic intervention) and, on the other hand, to have a system that can detect the variation in the state of certain HCIs.

The degree of naturalness of the territory is mapped and the methodology of development is through the analysis (Figure 15), on the one hand, of the physical reality of the territorial elements and, on the other hand, of the spatial relationships between these elements. Physical reality is analysed by assigning a degree of naturalness to each element and overlapping all the elements present. The spatial relationships between these elements are studied by means of a fragmentation analysis. The process takes into account the edge effect, in which naturalness is reduced the closer one is to an artificial element in a range of proximity from which naturalness is no longer lost. The barrier effect is also taken into account, in which the size of each natural fragment is analysed and the larger the fragment, or the greater the separation of artificial elements, the more natural it is. Finally, these two analytical phases of naturalness are related and statistically aggregated in a 20x20m grid.

The entities to which a degree of naturalness is assigned come from the following datasets:

- Integrated topographic map of the Canary Islands {Scale 1,000-5,000. Date EH:2016, LP:2016, LG:2018, TF:2017, GC:2019, FV:2018 and LZ:2017}.
- Street map {Scale 5,000. Date 2020}.
- Vegetation map of the Canary Islands {Scale 20,000. Date EH:2001, LP:2002-2003, LG:2002-2003, TF:1998-2000, GC:1998-2001, FV:2001-2005 and LZ:2000-2006}.

- Crop map of the Canary Islands {Scale 2,000. Date EH:2015, LP:2017, LG:2018, TF:2016, GC:2019, FV:2020 and LZ:2014}.

- Geological map of the Canary Islands. Scale 25,000. Date 2002-2005.

As a result of the process, the Naturalness Map of the Canary Islands is obtained [Figure 16], with integrated information on the physical reality described and the analysis of the spatial relationships that affect naturalness.

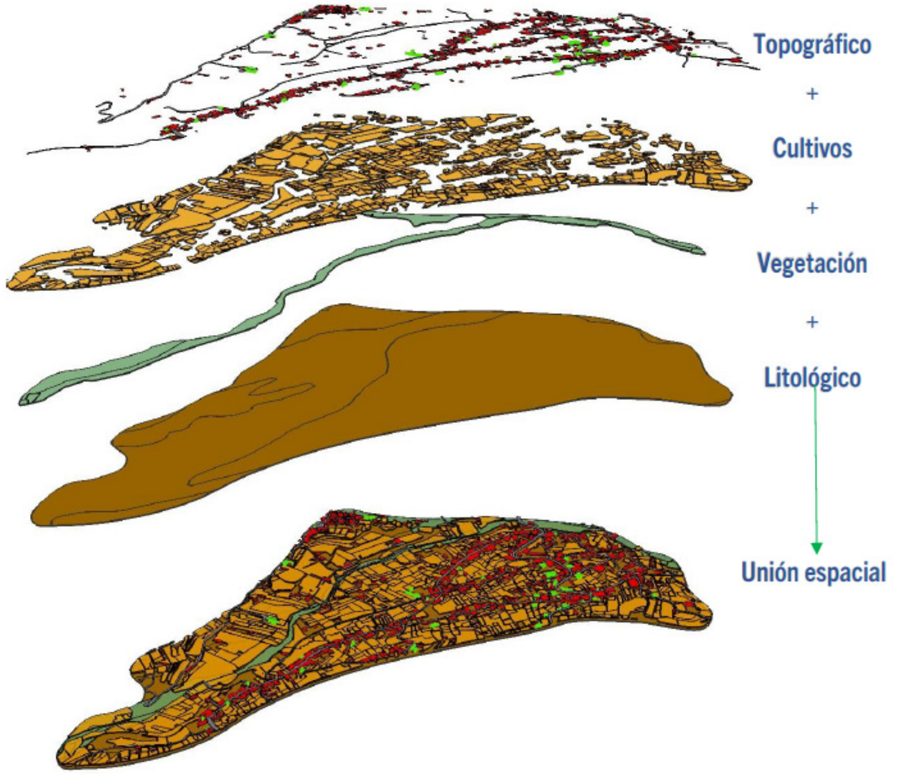

Figure 15: Spatial overlapping of the layers to obtain the geometric representation of the physical reality or ground plan of naturalness.

Since data sources of different scales have been used for the analysis of naturalness, it was considered appropriate to aggregate the data to a 20m grid. To characterise the naturalness of each square, a zonal statistic is performed that analyses the different naturalness values that fall within each of the 20m x 20m squares of the grid. As a result, the statistics [minimum, maximum, range, mean, standard deviation and sum] of the naturalness of each of the squares are obtained.

In summary, it should be noted that the Canary Islands Natural Map is a useful tool for the analysis of anthropic intervention in the territory [Figure 17], allowing the design of management actions aimed at the conservation of natural habitats, especially in the areas of the Canary Islands Network of Protected Natural Areas or the European Natura 2000 Network, and is being considered as a tool for the definition of new areas to be integrated. It is also very useful in the design of green corridors and in the analysis of ecological connectivity.

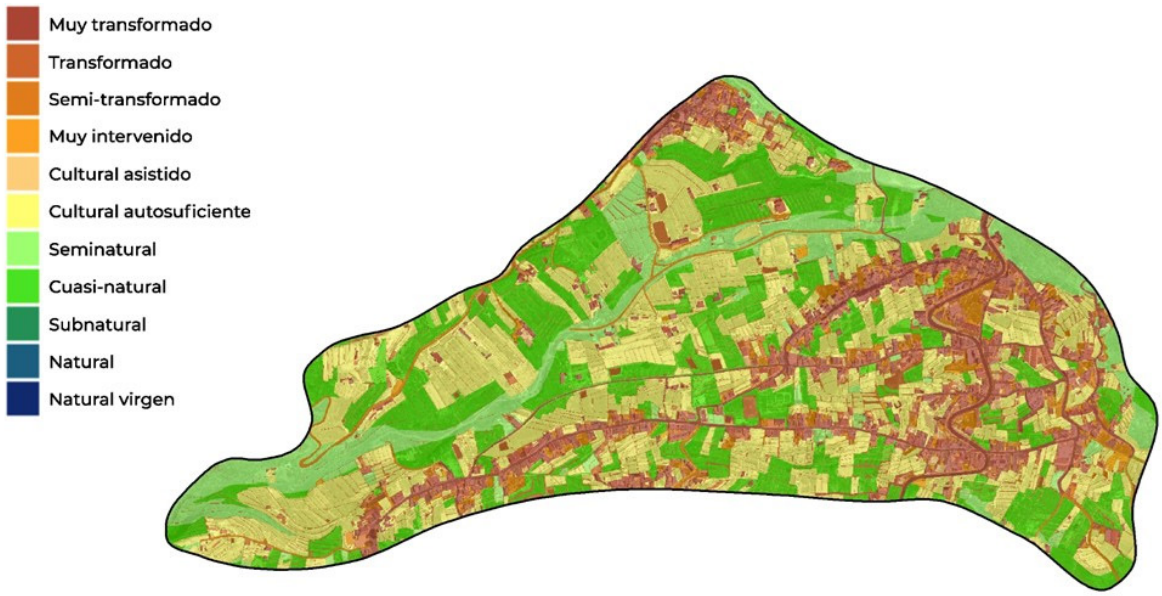

Figure 16: Example of naturalness of the material reality or ground plan.

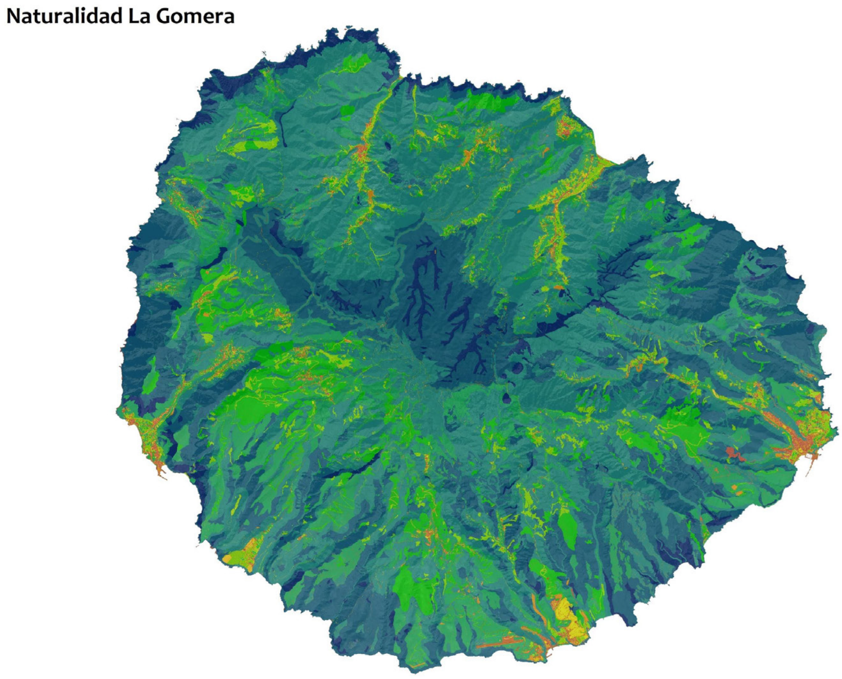

Figure 17: Example of a naturalness map in the case of the island of La Gomera.

For the monitoring of natural habitats, a methodology is being developed at different scale levels. On the one hand, it includes an inventory system of plants in plots of 20 x 20 m (or whole multiples of this), in which information is collected on three aspects: 1) the list of species and their assignment to the vegetation stratum in which they grow, 2) the cartographic projection of the cover of these species and 3) the number of individuals per development class. These inventories will be carried out on a regular basis (Figure 18).

On the other hand, after the selection of the most appropriate vegetation index, the Enhanced Vegetation Index (EVI) is used for all habitat areas, except for those with very small or sparse vegetation cover. This analysis is carried out with Sentinel-2 data and is conducted separately for habitat subtypes (which in many cases coincide with plant associations or homogeneous groups of them) and grouped by month, season and year. Previously, based on criteria of adequate representativeness and good state of conservation of these subtypes, reference areas are identified. Subsequently, the distances of the EVI values of each pixel from the values corresponding to the reference domains are quantified. EVI values are grouped into classes according to the distance of

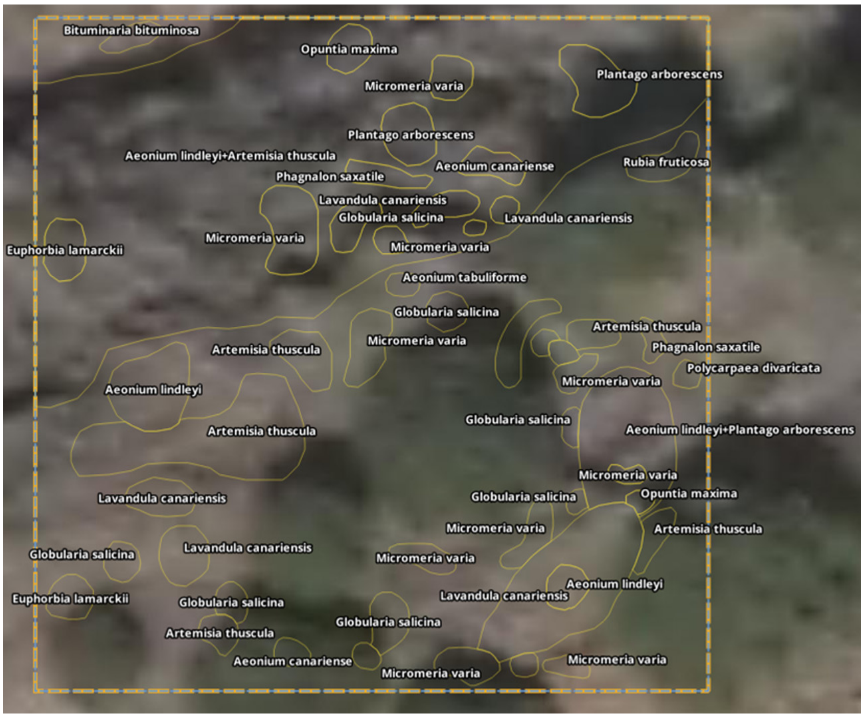

Figure 18: Examples of mapping obtained on a plot for two vegetation strata of the plot.

the value from the mean values of the reference domains [Figure 19].

As a result, maps of photosynthetic activity [a significant aspect of the "conservation status" of the community] are obtained with the values detected for each habitat subtype, referring to each year of the period for which Sentinel-2 data are available. The values obtained in these photosynthetic activity maps can be compared with the results of the inventories carried out as a ground truth supervision system.

Some of the processes are automated, and the execution of the processes is thus fast and homogeneous. The results can then be used to detect trends and set conservation alarms where values undergo significant sudden changes.

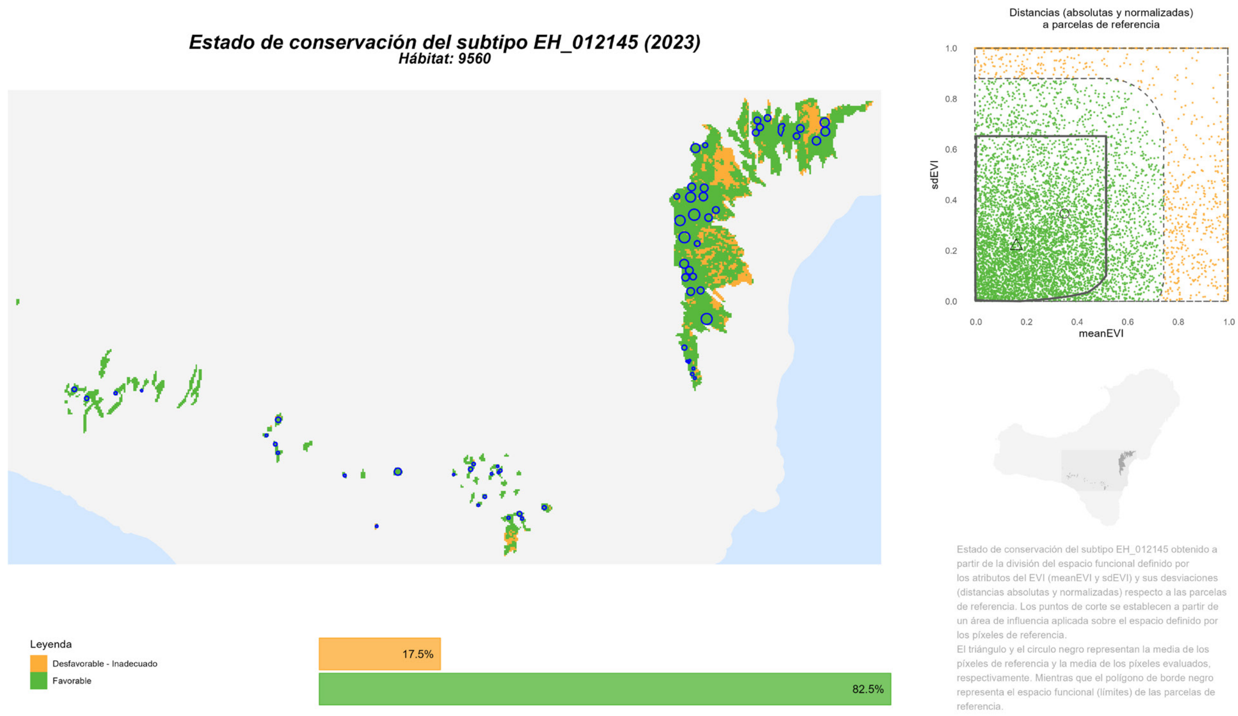

Figura 19: Exemplo de análise dos valores do EVI para um subtipo de habitat na ilha de El Hierro. Trata-se, para já, de um resultado preliminar e sujeito a pequenos ajustamentos metodológicos.

4. Coherence assessment

The preceding sections describe possible approaches to individually assessing five components, or indicators, of the ecological coherence of a conservation network such as the Natura 2000 Network. The next step is to combine these results to assess coherence as such.

In general, this type of procedure starts by applying a scale of values that transforms the objective results of an individual indicator into an assessment relevant to the issue at hand. For example, the percentage of the extent of an HCI's range within the Natura 2000 Network, relative to the entire known range, can be compared to a representation threshold internationally recommended for its conservation. The representativeness will then be assessed on an appropriate numerical scale (unfavourable - favourable, bad - fair - good, 0 - 10, etc.).

It is then necessary to combine the individual assessments in order to assess the state of the variable of the higher-level abstraction, in this case, network coherence. The procedure for this depends on the numerical scale of the individual indicators (qualitative, ordinal, quantitative, etc.), their reliability and accuracy, the heterogeneity and need for standardisation between individual indicators, and the intended usefulness for the overall assessment (legal, managerial, scientific, etc.).

In the work of Borja et al., (2014) a comprehensive review of individual indicator combination techniques was carried out. Some examples are: one-out all-out, averaging of individual indicators, weighted sums, multivariate methods, decision trees or conditional rules. Techniques that perform algebraic combinations of individual indicators are not considered to apply well in the case of coherence, where such indicators are heterogeneous in their calculation and metrics. Those that would be best applied include: the principle of one-out all-out, whereby all individual indicators must be favourable; the weighted sum of individual scores; and progressive high-level integration.

4.1. One-Out All-Out

The One-Out All-Out [OOAO] principle consists of conducting individual assessments of each indicator, giving a favourable result for the integrated assessment only if each of the individual ones is favourable.

This method confers equal importance on each individual indicator. The lack of weighting requires indicators to be homogeneous in terms of quality. On the other hand, it is understood that obtaining a favourable assessment is particularly difficult using this approach. This, which in principle would be a weakness, is in fact one of its greatest advantages: the method is conservative and cautious; accordingly, the favourable evaluations obtained in its application are solid.

For the above reasons, the OOAO method is selected when the outcome of the overall assessment may have legal or regulatory implications. For example, it is applied to assess Indicator 15.3.1 [Proportion of land that is degraded over total land area], which measures progress on Sustainable Development Goal 15.3 [Achieve a Land Degradation-Neutral World by 2030] [Orr et al., 2017]. Indicator 15.3.1 uses three sub-indicators to decide whether an area should be considered degraded: land cover or land use, land productivity and carbon stored [Sims et al., 2021]. All three are complementary in their time scales, and are therefore given equal importance. At the same time, each of them is backed up by a technical arsenal that makes it possible to accurately determine the state of the art of the relevant topic. Therefore, if any one of them fails to assess an area as non-degraded, that area is considered degraded regardless of the outcome of the others. Specifically, according to the OOAO principle, degradation occurs if soil organic carbon decreases significantly, or if Net Primary Production declines, or if a negative land use change takes place.

Another advantage of the OOAO principle is that the overall assessment can be disaggregated and sub-indicators can be examined separately, allowing corrective measures to be specified directly.

4.2. Weighted sum

This method uses a relatively long list of individual indicators, and assigns each one a score. The sum of the scores, ranked or unranked, is proportional to the integrated assessment sought. Individual indicators can be given different scores according to their relevance to the problem being assessed, which is equivalent to assigning weights to them. The procedure is used to assess both positive [e.g., conservation status] and negative [e.g. degree of threat] aspects.

This approach can be illustrated by the example applied by Camacho et al., [2019] to determine pressures and threats affecting lentic systems. They produced a list of 25 individual indicators, classified into 8 topics. The range of values attributable to each indicator depended on its importance as a threat. For example, “OCCASIONAL URBAN WASTEWATER DISCHARGE” can have a value between 3 and 20 points, while “THERMAL DISCHARGE” can only reach 2 points. The assessment matrix thus formed results in a total score, according to which the degree of threat is “LOW” [0 - 20 points], “MEDIUM” [21 - 50], “HIGH” [51 - 75] or “VERY HIGH” [> 75].

This method is flexible, as indicators can be scored differentially according to their perceived importance. At the same time, this flexibility can be arbitrary if it lacks explicit rules on the allocation of scores. This condition was present in the case cited as an example, and is essential for a realistic assessment.

4.3. Integrated approach

If the individual indicators are not homogeneous in terms of metrics, accuracy or reliability to reflect the proposed higher-level assessment, it is possible to use the conceptual model that led to the consideration of the use of such indicators. The premise here is that the indicators have functional relationships with each other, which can be exploited to gain a reasonable understanding of the higher-level problem.

In the case of the ecological coherence of the Natura 2000 Network, we propose five components which, far from being independent characteristics, are dependent on each other. This dependence can be seen in Figure 20.

To examine the coherence of the Natura 2000 Network with regard to the conservation of certain habitats. The first known fact is its observed distribution. However, it is necessary to recognise that the habitat may not have a uniformly good ecological status throughout its distribution. Therefore, it is necessary to examine Resilience, which will allow the exclusion of diseased, cleared or degraded areas, which should not be taken into account for the purpose of identifying areas for habitat conservation. This does not mean that areas in poor condition should be disregarded. On the contrary, they should be subject to special restoration or conservation. Nevertheless, counting them as an asset for assessing coherence carries the risk of overestimating the level of habitat conservation.

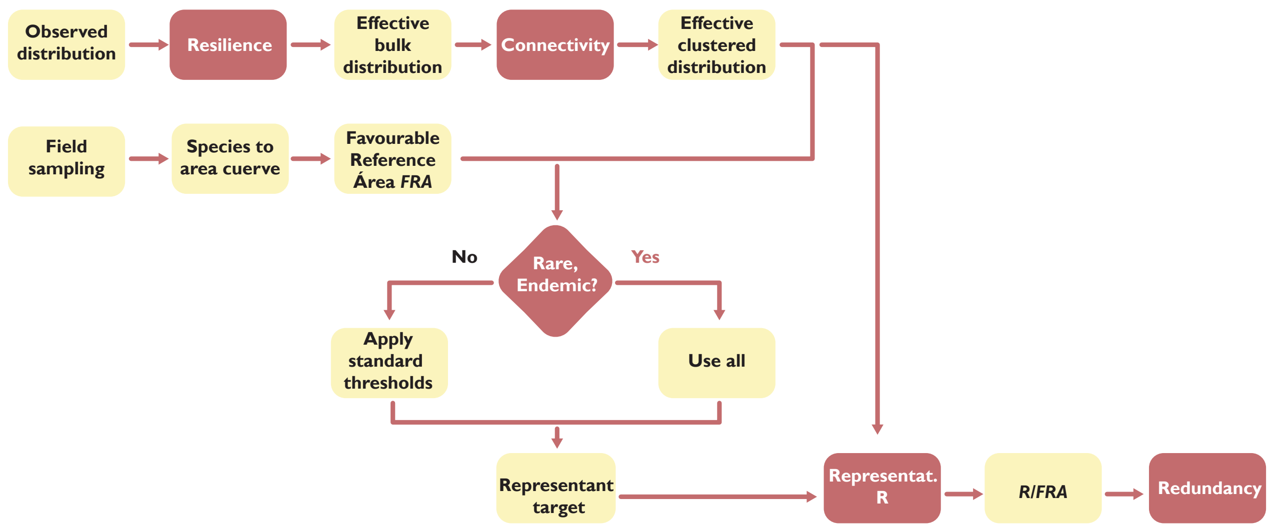

Figure 20. Information flow for an integrated assessment of the coherence of a conservation network.

The aforementioned exclusion leaves what could be called the effective raw distribution. But this is unrealistic, as any terrestrial habitat distribution exhibits varying levels of fragmentation, caused by the abiotic environment and/or human interventions. Some of the patches may have functional exchanges with the rest of the distribution, while others will be isolated and, while retaining their relict value, will contribute little to the persistence of the habitat in question. It is therefore necessary to conduct a Connectivity analysis in order to know the effective distribution in groups.

Not all patches in the latter distribution will be suitable for habitat conservation, even if they are connected to the rest of the distribution. Some may be too small and contain simplified versions where the habitat, while present, cannot fulfil its function as an umbrella for other species. This is where the concept of Favourable Reference Area [FRA, see Section 3.2.3] comes into play, which should have been experimentally determined by field sampling.

The effective distribution in groups, and the FRA allow the Rarity or Endemicity dilemma to be addressed. If the study habitat is neither rare nor endemic, international standardised thresholds can be applied to determine what extent of habitat, which should be part of the effective distribution in groups and which has patches larger than FRA, is effectively protected by the Natura 2000 Network. If the habitat in question is rare or endemic, then its entire extent must be within the Natura 2000 Network. Note that this dilemma applies whether the habitat has already been included in the Natura 2000 Network or is under consideration for possible inclusion.

In both cases of the above dilemma, the result is an R-value for Representativeness, which is the fraction of the habitat extent included in the Natura 2000 Network. At a minimum, the extent implied by R must be equal to FRA, otherwise the conserved territory would be unstable. In many cases, this extension will be several times greater than FRA. Therefore, the R/FRA ratio is proportional to the Redundancy of the amount of habitat preserved in the Natura 2000 Network.

4.4. Evolution

We must recognise that the problem of formally assessing the ecological coherence of the Natura 2000 Network is in its infancy. The problem has an intrinsically scientific part, with conceptual challenges imperfectly resolved around some of the components of coherence, e.g. connectivity or resilience. In addition, there is a political side, whereby public administrations will have to make significant investments, some at a not inconsiderable opportunity cost, to improve the coherence of the Natura 2000 Network. Finally, there is a legal aspect, associated with regular reporting to the EU on the status of coherence of the Natura 2000 Network.

The integration methods outlined above are considered to have followed a desirable order of preference. However, the compiling of the scientific, the political and the legal aspects would probably not stand up to an OOAO-type scheme. For this reason, it is suggested to go from the bottom-up. The integrated approach is at the same time conservative enough to ensure a realistic assessment of coherence, and transparent enough to identify errors and inconsistencies in the methodology. Only when this phase has been overcome, it may be appropriate to explore a procedure based on weighted sum, which allows for the assessment of various aspects that are already implicit in the conceptual model. And finally, decisions with legal implications should be based on an OOAO assessment of the Natura 2000 Network ecological coherence.

4.5. Management levels and spatial domains

Having established the components of coherence and how to assess coherence, it is necessary to point out how these aspects can be addressed at the management level. As seen in previous chapters [2.3 Spatial reference units and domains], the current management of the Natura 2000 Network is carried out solely through management tools at site level. It includes the goals and measures for the HCIs and SpCIs present, without taking into account the relationships they have with the rest of the sites that make up the Natura 2000 Network through the properties of coherence, nor with the HCIs and SpCIs present in the Biogeographical Region and which are not included in the Natura 2000 Network sites.

The analysis of each of the properties of coherence is first carried out at the level of the Biogeographical Region. For example, representativeness is one of the properties that has been considered from the outset, as it is included in Annex III of the Habitats Directive. In the case of Spain, [Orella et al., 1998] analyse in detail the representativeness criteria used for both HCIs and SpCIs at the time of the creation of the Natura 2000 Network.

This leads to the first level of the management hierarchy: the site management instrument, which is legally binding in Spain. Integrating the individual representativeness assessments allows the uniqueness of each site within the whole Natura 2000 Network to be assessed for the relevant spatial domain. In addition, for this assessment to be complete, it is necessary to have an analysis of the rest of the coherence properties across the entire spatial domain of the Biogeographical Region.

The next step introduces the need for management instruments at higher levels, where this assessment of representativeness and the other parameters of coherence can be carried out. This higher level is defined by the Habitats Directive itself and corresponds to the Biogeographical Region. The Biogeographical Region is the responsibility of the EU, through the European Environment Agency or the European Topic Centre on Biodiversity [ETC/NC], and should at least set the overall objectives for achieving coherence across the five components. It is also crucial to explore links with HCI and SpCI Action Plans, such as the one currently being developed in the Macaronesian Region for laurel forests.

The need for this level is reinforced by rapidly changing climatic conditions, which requires dynamic conservation networks that take into account resilience and connectivity and set targets and measures to enhance these properties in each Natura 2000 site and beyond. In order to set these objectives and measures beyond sites, it is necessary to have management instruments that apply to larger spatial domains such as the Biogeographical Region.

At these two levels, site and Biogeographical Region, the relevant management instrument must include a diagnostic section containing an analysis of each of the coherence parameters and, for the Biogeographical Region, an additional coherence assessment in the terms set out in the previous sections. The result of this diagnosis should lead to the setting of objectives to be achieved, in relation to each of the components of coherence, in the period of validity of the management instrument, which it would be advisable for it to coincide with the six-yearly reports established in the Directives. In turn, these objectives should be detailed through the development of the necessary measures to achieve them.

However, in terms of analysing the connectivity of terrestrial HCIs and SpCIs, in a region such as the Macaronesian region, made up of oceanic volcanic islands, it would make sense to carry out assessments mainly in the island domain.

The assessment of each of the five properties that make up coherence is applied to a spatial domain and its relevant management level. However, overall coherence requires levels above the sites, which will depend on the political-administrative organisation of each Member State and how management responsibilities are distributed at each level.

The management of the Natura 2000 Network in Spain falls within the responsibility of Autonomous Communities, and some of them have delegated the management of the sites to administrations of lower territorial rank, as in the case of the Canary Islands, where the responsibility for the management of the Natura 2000 Network sites lies with the Island Councils.

However, the responsibility for the management of habitats and species outside the sites has not been delegated to the Island Councils, so it remains with the Canary Islands Government, which also maintains the responsibility to report on their conservation status to the Ministry of the Environment [currently MITERD]

The management and implementation of the Natura 2000 Network in mainland Portugal is the responsibility of the Institute for the Conservation of Nature and Biodiversity, while the

management of the existing Natura 2000 Network areas in the Autonomous Regions of the

Azores and Madeira are the responsibility of the respective Regional Governments.

The management of Natura 2000 sites in the Autonomous Region of Madeira is the responsibility of the Regional Government, through the Instituto das Florestas e Conservação da Natureza, IP-RAM [IFCN IP-RAM]. The institute's mission is to promote nature conservation and to sustainably plan and manage terrestrial and marine biodiversity, landscapes, forests and associated resources. The IFCN, IP-RAM is the regional authority responsible for the management of protected areas and Natura 2000 sites, both on land and in territorial waters. In doing so, it works with a variety of partners who understand regional realities and challenges, including other public administration bodies, municipalities, associations, NGOs and other authorities.

The management tasks of the Natura 2000 Network in the Autonomous Region of the Azores are carried out by the departments of the Regional Government of the Azores with responsibility for the environment and the sea, namely the Regional Directorates for the Environment, Climate Action and Sea and Fisheries.

Given the variety of situations arising from the implementation of the Natura 2000 Network in the Autonomous Region of the Azores and the need to adopt a management model based on standardised criteria that unifies the various protected area designations, it was decided to concentrate responsibilities in an island territorial unit or maritime area as basic management units. Therefore, the legal regime for the classification, management and administration of Protected Areas in the Region was reformulated by means of a Legislative Decree establishing the legal framework for nature conservation and biodiversity protection. This resulted in a Network of Protected Areas of the Azores, where the sites of the Natura 2000 Network are integrated, based on the classification of the International Union for Conservation of Nature [IUCN], adapted to the geographical, environmental, cultural and political-administrative particularities of the territory of the Azores archipelago.

This distribution of responsibilities in the management of the Natura 2000 Network leads us, in the case of the Macaronesian Region, to add, between these two levels of management, other possible levels, marked both by the political-administrative organisation [Member States and autonomous regions/communities] and by the geographical configuration [the islands]. Thus, levels such as the state level [Spain and Portugal], the autonomous region/community level [Canary Islands, Madeira and Azores] and the different island levels, if necessary, could be considered.

In summary, it seems reasonable, in an archipelagic biogeographical region, to introduce levels of management that include the site, the island and the Biogeographical Region. The political-administrative level only makes sense from the perspective of organising responsibilities and not from an ecological perspective. This would be done through the aggregation of the island levels, reflected in a management instrument that includes this administrative division, or through a management instrument at archipelago level, which in the case of the Canary Islands makes sense as the responsibility for managing the sites falls on the island administrations [councils].

The engagement of the European Commission is also crucial in the development of management instruments at the Biogeographical Region level, to analyse each component of coherence and to set specific objectives for that spatial domain. Then, through aggregation, targets would be set at the necessary administrative levels of management: autonomous region/community and member state.

An additional aspect provided by this hierarchical system of planned management is the need for greater coordination between administrations, as this is the only way to develop management instruments covering different administrative areas.

The need for a multilevel and hierarchical planned management system [waterfall methodology] for protected areas has already been advanced in the document Planning to manage protected natural areas [EUROPARC-España, 2008] where it was pointed out that the planning instruments of the higher levels guide and coordinate, but do not replace, the plans of the lower levels, and the lower-level plans, as they are developed, allow the objectives of the higher plans to be improved and nuanced.

5. Geospatial data required

Most of the technical approaches presented in the preceding sections make significant use of geospatial data and geomatics techniques. This is considered the best way to obtain objective, explicit, repeatable and updatable results. Expert criteria are systematically incorporated into the procedures, and this allows their impact to be accurately assessed. The results thus obtained can be considered as a starting point for assessing the relevant conservation scenarios.

This methodological scheme can only be maintained if some geospatial resources are available. This section describes some of them which, while essential for the issue addressed herein of assessing the coherence of the Natura 2000 Network, are equally useful in a more general way for territorial management of the sites that make up the network.

5.1. Network of field plots with species inventories

Several sections of this document mention the need to use field data to obtain essential information on HCIs. An example of this is the determination of the Favourable Reference Area [FRA] in Section 3.2.3, which is a multi-purpose parameter for the management of the Natura 2000 Network and which, in this paper in particular, is applied to estimate the redundancy with which an HCI is represented in the network. Another example is the case study on naturalness and HCI monitoring in the Canary Islands, which describes a permanent sampling network to assess the degree of anthropic intervention and to monitor the status of HCIs in this archipelago.

In general, a permanent sampling network, consisting of plots that are visited over time, is an essential resource for managing the Natura 2000 Network. Such a system should serve multiple purposes, and therefore have a background activity on which specific campaigns can be run. Some objectives of such a network include: understanding the composition of biological communities linked to local variants of the HCIs represented; detecting variations in biotic [e.g. presence of invasive species] or abiotic [e.g. pollution] conditions that may have significant impacts on the persis- [illegible] of the ecosystems to be conserved; serving as on-site control points [illegible] ne or remotely sensed ground observation campaigns; and ser- [illegible] tial support for sampling campaigns of ecological variables [e.g. [illegible] net primary production].

The sampling design could be stratified following an analysis of the main sources of environmental and ecological variation, and include plots both inside and outside the Natura 2000 Network. This would allow a first level of monitoring, consisting of continuously assessing the performance of the Natura 2000 Network under the assumption that the land should be in a better condition inside than outside the network sites.

The spatial sampling units [SSUs] should be consistent with the spatial resolution of one or more Earth Observation systems considered for incorporation as a complement to the sampling network. For example, Sentinel-2 is a natural candidate for providing data, and its optical spectral configuration includes four bands at 10 m, six at 20 m and three at 60 m spatial resolution. Therefore, from this point of view, the SSUs should consist of nested plots whose side is a multiple of 10 m. This is the case of the system adopted in the Canary Islands, which consists of plots of 20 m on each side.

This size is manageable for a field team and compatible with a georeferencing system that does not require the use of differential GPS procedures [although these are always preferable]. The plots should be separated by a distance greater than a spatial autocorrelation value determined by a previous campaign.

The data to be recorded in these SSUs should be subject to careful planning beyond the scope of this document. It would probably be helpful to distinguish three categories: a single campaign [e.g. complete species inventory of selected groups and taxa, to determine the FRA additively]; regular campaigns [e.g., environmental monitoring data] and specific campaigns [e.g., calibration of vegetation indices with biomass or production data].

5.2. Observed habitat and species distributions

An atlas showing the distribution of HCIs and SpCIs in a certain Natura 2000 management area is, almost by definition, the main sign of the Network's identity in that territory. In an archipelagic region such as the Macaronesia, the areas are at least that of an island and that of a biogeographical region. The ultimate purpose of such an atlas is to show where the HCI or SpCI occurs.

This fact is important on its own, and in conjunction with proper monitoring, is vital to indicate the health and persistence of the Natura 2000 Network over time. However, it is also the natural dependent variable for obtaining predictive distribution models, which have applications in problems as diverse as identifying restoration projects, evaluating climate change scenarios, applying connectivity models or estimating resilience.

It is therefore necessary to couple the resolution of observed HCI and SpCI distribution maps with that of predictor variables that can be used in modelling exercises. For example, kilometre resolutions will allow the fitting of climate models that respond to relief mesoforms. However, if the predictive potential of topography is to be explored, the resolution should be increased to decametre or even metre resolution. Naturally, this depends on the modelling objectives, which are, in turn, conditioned by the geographical setting and the size of the area of study.

Where possible, it is advisable that observed habitat and species distributions are in digital format and follow recognised standards for documentation and management. Applications such as ModestR [García-Roselló et al., 2013] can help for these purposes.

5.3. Climate variables

The bioclimatic variables, as outlined throughout this guide, are derived from monthly temperature and precipitation values to generate more biologically meaningful variables. These can be obtained through various formulae (O'Donnell and Ignizio, 2012; Xu and Hutchinson, 2016), using tools such as the biovars function (Hijmans et al., 2011) or simply using variables already generated by other authors.

If the 19 bioclimatic variables are to be used, in the simplest way, it is recommended to use the CHELSA variables (Karger et al., 2017), as they cover a period closer to the present (1980-2010) than other databases such as WorldClim (1970-2000). However, the generation of these variables with R (biovars, dismo) is recommended, adapting the appropriate time period.

Of course, scale in climate data has been widely noted in capturing heterogeneity. This methodology is also feasible on the basis of the microclimate, which is feasible in the islands of the Macaronesian region, but not on a European or even peninsular level. There are multiple mechanistic models for estimating microclimates (Maclean et al., 2019). In addition, it is important to pay attention to discontinuities between composite weather variables (Booth, 2022), i.e. some bioclimatic variables.

Nombre	Periodo	Resolución	Cita
WorldClim	1970 - 2000	- 1 km^2	Hijmans *et al.*, 2005
Chelsa	1901 - 2016/2019	- 1 km^2	Karger *et al.*, 2017
Envirem	1981 - 2010	- 1 km^2	Title & Bemmels, 2018
EuMedClim	1901 - 2014	- 1 km^2	Fréjaville & Benito Garzón, 2018
Terraclimate	1958 - 2020	- 5 km^2	Abatzoglou *et al.*, 2018
ERA5	1950 - 2024	- 5 km^2	Muñoz Sabater *et al.*, 2018

Table 3. Different sources of climate data are presented in order to develop the assessments proposed throughout the guide

5.4. Biblioteca de distribuições preditivas de habitats

A library of potential distribution models of priority habitats could be a great help in analysing the coherence of the Natura 2000 Network because of its excellent capacity to identify suitable unoccupied areas, optimise habitat restoration, assess climate change scenarios, and parameterise connectivity models. Library means a set of models that have been previously developed or are available to be run. The library could be set up in three different ways:

- Priority habitats can be modelled following standard procedures (see below) and their results (either in the form of images or as R statistical language objects) stored in an online repository available to the public or to entities with nature conservation responsibilities. Such a repository provides images, and anyone could use and interpret them, regardless of their knowledge of ecological niche models (also called potential species distribution models). On the contrary, if the repository provides R objects, the user would have to be familiar with the R environment and with some packages with spatial functions (e.g., terra) (Sillero et al., 2023), in order to visualise the objects and extract information from them.

- - If more flexibility in modelling habitats is required (e.g. a specific combination of environmental variables), already developed modelling applications such as wallace 2 (Kass et al., 2023) could be used. This application is written in R using the Shiny package, to create the online platform. The wallace 2 website guides the user through the modelling process, which already integrates standard modelling procedures, indicating which data to enter and which parameters to select. The application is intuitive and very efficient. Wallace 2 provides the basic results of the models. It is also possible to use other software, such as ModestR (García-Roselló et al., 2013), which accompanies the user during modelling and does not require computer skills. The user will need a minimum of modelling knowledge to be able to use any online platform and interpret the results.

- -A third option could be the development of a proprietary application that implements the modelling process in a way that is specific to the wishes and needs of the project. This application can be developed in R language through the Shiny package, or in Google Earth Engine (GEE) (Gorelick et al., 2017). There are different platforms already available that could serve as an example to follow, such as wallace 2, mentioned in the previous point. Such an application could integrate a single algorithm (e.g., Maxent) (Phillips et al., 2006, 2017) or several, so the final result would be an aggregation (e.g. ensemble forecasting) (Araújo and New, 2007) of several algorithms (similar to the biomod2 package) (Thuiller et al., 2009, 2003). In this case, the knowledge required by the user may be greater or lesser depending on the degree of automation and parameterisation of the application. The application may require the user to have a greater or lesser say in how the models are to be calculated. In any case, the user should always have some knowledge of ecological niche modelling. The user could choose the intended habitat, the most suitable environmental variables, the modelling algorithm (or several of them), and define the most essential parameters. The application would provide the map with the potential distribution of selected habitat, together with the response curves of the environmental variables, and the contribution of each of them to the model.

Regardless of the solution chosen, ecological niche models (Sillero, 2011) should be calculated following standard procedures (Sillero et al., 2021; Sillero and Barbosa, 2021). These procedures are usually divided into four phases: data collection and preparation, and model calculation, validation, and application. In summary:

1. 1. Data collection and preparation:

1.1. *Compilation of species occurrence data (in this case, habitats) and environmental variables.* Occurrence data can be obtained from fieldwork, museum records, or existing databases (analogue or digital). Environmental variables must be related to the distribution of the habitat or species in question, such as temperature, precipitation, elevation, land use, potential vegetation, soil type, soil chemical conditions (pH), etc. It is best if the variables represent important boundaries for the species to be modelled. It is these types of environmental variables, which mark the range of the species, that must be entered into the models. Elevation can also be a good choice, because it is a proxy for many other environmental variables, especially if the species has a restricted range. However, elevation alone may not be a restricting factor in the distribution of the species. It is not possible to define a set of variables a priori because this will depend on the habitat or species to be modelled, the variables available in the study area, and the correlation between variables (see section 1.4). Currently, there are many digital repositories offering a wide range of environmental variables (Sillero et al., 2021). GEE (Gorelick et al., 2017) is a good option as it compiles all public Earth Observation programmes (Landsat, MODIS, Sentinel) and provides the necessary analytical tools. For example, it is already possible to calculate ecological niche models with Maxent (Campos et al., 2023) or Random Forest (Crego et al., 2022). There are more repositories of terrestrial environmental variables (WorldClim (Fick and Hijmans, 2017); CHELSA (Karger et al., 2017; Kreft et al., 2017); EuMedClim (Fréjaville and Garzón, 2018)) than marine (Bio-oracle (Tyberghein et al., 2012); Marspec (Sbrocco and Barber, 2013)).

1.2. *Cleaning and pre-processing of distribution data*. This involves eliminating duplicate records and correcting both spatial (coordinate errors) and other errors (specific identification errors, name errors). Some algorithms only need data indicating the occurrence of the species, or the presence and sampling conditions available in the area of study (background data), or presence and absence data.

1.3. *Definition of the shape and extent of the area of study. Variables will be trimmed by the area of study.* The area of study is not easy to define (Sillero et al., 2021): it is convenient to exclude those areas within the study area that have appropriate characteristics for the occurrence of the species, but which the species cannot reach. It is advisable not to use administrative boundaries as long as they do not correspond to biogeographical boundaries. The use of biogeographical regions is the simplest solution to define the area of study. In the case of islands, the area of study may well be the entire island because they function as closed systems. The extent of the study area defines the type of environmental variables that can be introduced into the models. To obtain an ecological niche model, an environmental gradient in the study area is necessary: the stronger the environmental gradient, the easier it is to model the distribution of the species. This means that when modelling over very large areas of study, the environmental gradient will be mainly climatic, and therefore climate variables will have to be introduced into the model. However, if the area of study is very small, there will not be a climatic gradient (temperature will be the same or very similar throughout the area of study), but the environmental gradient will correspond to other environmental variables such as topography or prey abundance. Therefore, the size of the study area conditions the predictor variables.

1.4.*Selection of environmental variables.* Variables with a higher correlation (usually higher than |0.7|) should be excluded from the process. In addition to calculating the correlation between them, it is recommended to measure the degree of collinearity with the VIF - Variable Inflation Factor. The VIF should never be higher than 5.

2. Calculation of the model:

2.1.*Data partition*. Habitat occurrences should be divided into training data (to estimate the model) and test data (to assess the model). The ratio between the two data sets is usually 70/30%. The smaller the sample size of the two groups, the more similar the ratio should be. In the case of using attendance and absence data, the partition is applied to both groups of records with the same proportion.

2.2. Selection of the correlative modelling algorithm. As indicated above, not all algorithms require the same distribution data (Sillero et al., 2021):

2.2.1. Presence-only algorithms, such as Bioclim (Booth et al., 2014) or Domain (Carpenter et al., 1993).

2.2.2. *Algorithms that use presence and background data, such as ENFA (Hirzel et al., 2002) or Maxent (Phillips et al., 2006, 2017).* In this regard, it is important to note that background data are not comparable to pseudo-absences (i.e. artificially created absences), as they are extracted from the entire area of study (Guillera-Arroita et al., 2014; Sillero and Barbosa, 2021).

2.2.3. Algorithms using presence and absence.

2.3. Calibration (calculation) of the model: The selected algorithm calculates the model with the training data and the environmental variables. This involves adjusting the model parameters to maximise predictive accuracy. Each algorithm has its own set of parameters (Sillero et al., 2021). As the partitioning of training and test data is done randomly, it is necessary to replicate the model several times (a minimum of 10) to analyse the effect of partitioning variability. The result of the replication of the models is the average model and its standard deviation. It is also possible to calculate several algorithms to obtain a final average (ensemble forecasting) (Araújo and New, 2007).

3 Assessment of the model: The performance of the model is assessed with the test data. Common discrimination metrics include Area Under the Curve: AUC) of the Receiver Operating Characteristics (ROC) curve, and the True Skill Statistic (TSS).

4. Application of the model: Overlaying the model on other sources of environmental data to aid interpretation.

Modelling species is relatively simple, but modelling habitats is not the same. Ecological niche models are initially intended to model species (or other taxonomic levels) and not habitats (Sillero, 2011; Sillero et al., 2021; Smith et al., 2019). There are tens of thousands of examples of species models (Anderson, 2012), but habitat models such as those by Marquez Barraso et al. (2015) are much less common. In fact, these models essentially refer to forest types defined by a few species, which facilitates their identification as a separate entity. Ecological niche models identify which habitats a species prefers, but not the environmental conditions preferred by the habitat: in other words, habitats when modelled are treated as if they were a species. However, habitats are easy to map, because they can be easily recognised (classified) with satellite images (Nagendra, 2001).

In order to model HCIs with ecological niche models, there are two options:

- oCollect environmental data at locations where the HCI under study exists. In this case, the model is calculated from a table where the coordinates of the locations are not necessary. The only thing required is the table with the data on the environmental variables for each presence and absence of the habitat. The result is not spatial. A map of the model can be obtained if the environmental variables included in the model exist in digital format. Thus, the model formula can be applied to the rasters of the environmental variables.

- From a digital polygon map of the HCI under study, create random points on each polygon (only one point per pixel). Once habitat occurrences are obtained, they can be modelled in a traditional way with currently available tools (Sillero et al., 2023).

6. APPENDIX: current data on Macaronesian terrestrial habitats

According to the latest Reference List, dated December 2022, the EU Terrestrial Macaronesian Region comprises 39 Habitat Types of Community Interest (HCI). Only twelve of them are represented in both Member States (Spain and Portugal), and five are found only in this region (Table A1).

The sum of 39 HCIs are distributed among the following groups: coastal habitats and halophytic vegetation (9), maritime and terrestrial dunes (3), freshwater habitats (5), temperate heath and scrub (3), sclerophyllous scrub (1), natural and semi-natural grassland formations (2), bog and marshy areas (4), rocky habitats and caves (5) and forests (7). Of these, 9 are considered a priority, 4 of which belong to the forest group. There are 20 types in Spain and 30 in Portugal, distributed between the archipelagos of the Azores and Madeira.

Table A1. List of Terrestrial Habitat Types of Community Interest present in the Macaronesian Community Region. In light blue the habitats of priority interest common to the two member states, in dark blue those present in the three Macaronesian archipelagos and in bold those exclusive to this region. Obtained from: EIONET latest version updated in December 2022.

The data provided by the participating Member States on the detailed distribution and area of occupancy of the different HCIs, whether marine or terrestrial, present in the Macaronesian region are described below (Table A2). This table does not include HCIs 1140 and 7220, as, although they are both included in the latest reference list, none of the Member States that make up the Macaronesian region have included them in their report under Article 17 for the last six-year period.

Table A2. Distribution and area of occupancy of HCIs in the EU Macaronesian region.

You can consult the table using the following link: [link: https://trabajos-diseno.tragsatec.es/descargas/distribucionHCI.zip](https://trabajos-diseno.tragsatec.es/descargas/distribucionHCI.zip)

In terms of land area, the three HCIs with the greatest extension in the Canary Islands are: 9550 Canarian endemic pine forests (73,698.37 ha), 5330 Thermo-Mediterranean and pre-desert scrub (57,198.53 ha) and 4050 Endemic Macaronesian heaths (*) (32,572.76 ha). Less information on terrestrial habitats is available for Madeira. Based on the information provided by the representatives of the region, the terrestrial habitats that occupy the largest known area are: 9360 Macaronesian laurel forests (*) (17,008 ha), 1250 Vegetated sea cliffs with endemic flora of the Macaronesian coasts (12,000 ha) and 5330 Thermo-Mediterranean and pre-desert scrub (8,400 ha]. Finally, in the Azores, the most extensive habitats are: 4050 Endemic Macaronesian heaths [*] [9,715.80 ha], 7130 Blanket bogs [* if active bog] [6,985.47 ha] and 9360 Macaronesian laurel forests [*] [5,880.81 ha].

For marine habitats, surface area data are only available for these habitats in the Azores: 1170 Reefs [4,580,000 ha], 1160 Large shallow inlets and bays [610,000 ha] and 8330 Submerged or partially submerged sea caves [76,000 ha].

With regard to the total area per island, the data collected reveal some interesting results. In the Canary Islands archipelago, Tenerife has the highest number of HCIs [18], most of which are partially protected under the Natura 2000 Network. Only 4090 Endemic oro-Mediterranean heaths with gorse are fully protected in Natura 2000 sites. The Canary Island with the lowest representation of HCIs is La Graciosa [5], the smallest of the archipelago, with all HCIs partially protected under Natura 2000.

In the archipelago of Madeira, the island of Madeira has the highest representation of HCIs, with a total of 11. All those for which data are available have partial European protection, except 2130 Fixed coastal dunes with herbaceous vegetation ['grey dunes'] [*], 3130 Oligotrophic to mesotrophic standing waters with vegetation of the Littorelletea uniflorae and/or of the Isoëto-Nanojuncetea and 3170 Mediterranean temporary ponds [*], all of which are included in the Natura 2000 Network. Savage Islands contain the smallest number of HCIs in the archipelago, with only 3 HCIs, fully protected under Natura 2000.

In the Azores, the islands with the highest representation are Terceira and Pico, with 26 HCIs each, while Graciosa and Santa Maria have the lowest number, 10 and 11 respectively. In many cases, it has not been possible to collect data on the surface area of HCIs outside and inside Natura 2000 sites. Based on the data provided, only the islands of Corvo, Flores, Terceira and S. Jorge have at least partially protected all HCIs in Natura 2000 sites, and there is no case in the whole Azores archipelago where 100% of an HCI is fully protected under Natura 2000.

THIC	Description	Habitat group	Annex I priority	Presence		
				Canarias	Azores	Madeira
1140	Mudflats and sandflats not covered by sea water at low tide M	Coastal habitats tats				X
1150	Coastal lagoons	Coastal habitats	*	X	X	
1160	Large sh Large shallow inlets and bays allow inlets and bays	Coastal habitats			X	
1210	Annual vegetation of drift lines	Coastal habitats		X	X	
1220	Perennial vegetation of stony banks	Coastal habitats			X	
1250	Vegetated sea cliffs with en-demic flora of the Macaronesian coasts	Coastal habitats		X	X	X

1320	Spartina swards [*Spartinion maritimae*]	Coastal habitats			X	
1410	Mediterranean salt meadows [*Juncetalia maritimi]*	Coastal habitats			X	
1420	Mediterranean and thermo-Atlantic halophilous scrubs [*Sarcocornetea fruticosi*]	Coastal habitats		X		
2110	Embryonic shifting dunes	Dunes habitats		X		
2120	Shifting dunes along the shoreline with Ammophila arenaria [*'white dunes'*]	Dunes habitats		X		
2130	Fixed coastal dunes with herbaceous vegetation [*"grey dunes'*]	Dunes habitats	*	X	X	X

3130	OligotroptHIC to mesotroptHIC standing waters with vegetation of the *Littorelletea uniflorae and/or of the Isoëto-Nanojuncetea*	Freshwater habitats			X	X
3150	Natural eutroptHIC lakes with *Magnopotamion or Hydrocharition — type vegetation*	Freshwater habitats		X	X	X
3160	Natural dystroptHIC lakes and ponds	Freshwater habitats			X	X
3170	Mediterranean temporary ponds	Freshwater habitats	*		X	X
3220	Alpine rivers and the herbaceous vegetation along their banks	Freshwater habitats			X	X

4050	**Endemic macaronesian heaths**	**Heath & scrub**	*	**X**	**X**	**X**
4060	Alpine and Boreal heaths	Heath & scrub			X	
4090	Endemic oro-Mediterranean heaths with gorse	Heath & scrub		X		
5330	**Thermo-Mediterranean and pre-desert scrub**	**Sclerophyllous scrubs**		X	X	X
6180	Macaronesian mesophile grasslands	Grasslands			X	X
6420	Mediterranean tall humid grasslands of the *Molinio-Holoschoenion*	Grasslands		X		

7110	Active raised bogs	Bogs, mires & fens	*		X	
7120	Degraded raised bogs still capable of natural regeneration	Bogs, mires & fens			X	
7130	Blanket bogs [* if active bog]	Bogs, mires & fens			X	
7140	Transition mires and quaking bogs	Bogs, mires & fens			X	
7220	Petrifying springs with tufa formation [Cratoneurion]	Bogs, mires & fens	*	SR		
8220	Siliceous rocky slopes with chasmophytic vegetation	Rocky habitats		X	X	X

8230	Siliceous rock with pioneer vegetation of the *Sedo-Scleranthion or of the Sedo albi-Veronicion dillenii*	Rocky habitats			X	X
8310	Caves not open to the public	Rocky habitats		SR	X	
8320	Fields of lava and natural excavations	Rocky habitats		X	X	
9320	*Olea and Ceratonia forests*	Forests		X		X
9360	**Macaronesian laurel forests *[Laurus, Ocotea]***	**Forests**	*	**X**	**X**	**X**
9370	Palm groves of *Phoenix*	Forests	*	X		

9550	**Canarian endemic pine forests**	**Forests**		**X**		
9560	Endemic forests with *Juniperus* spp.	Forests	*	X		X
91D0	Bog woodland	Forests	*		X	
92D0	Southern riparian galleries and THICkets *[Nerio-Tamaricetea and Securinegion tinctoriae*]	Forests		X		

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