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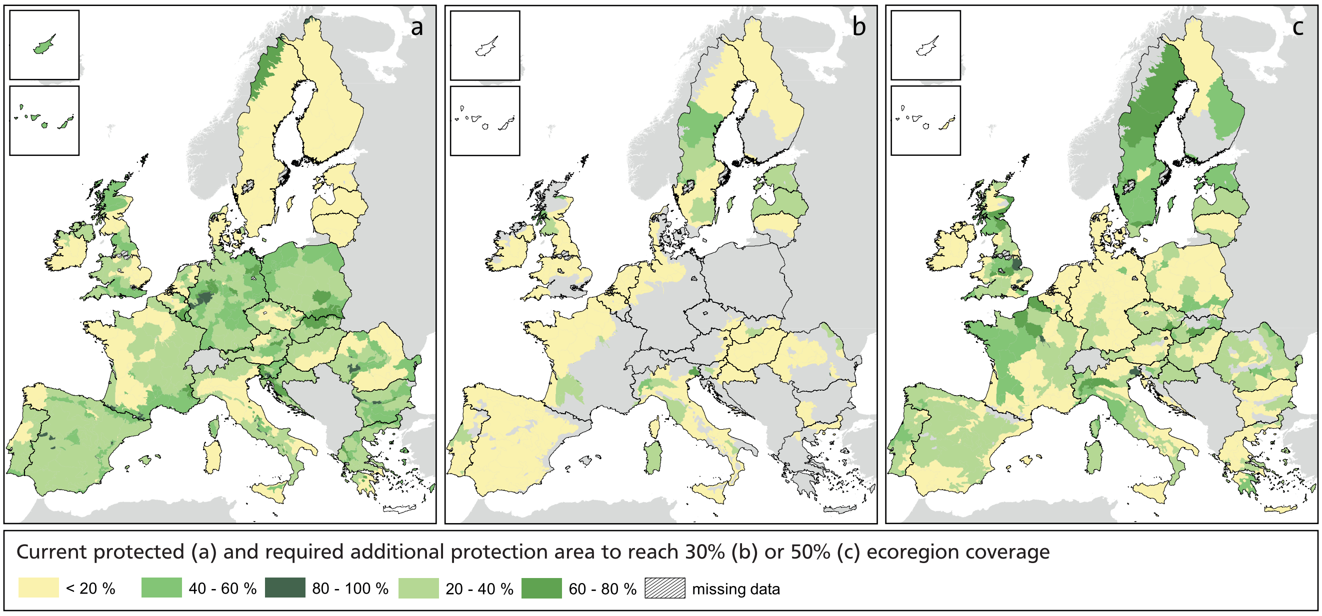
Evaluating and systematically improving the European Union's nature protection network towards current and potential ecoregion representation targets



Anke Müller

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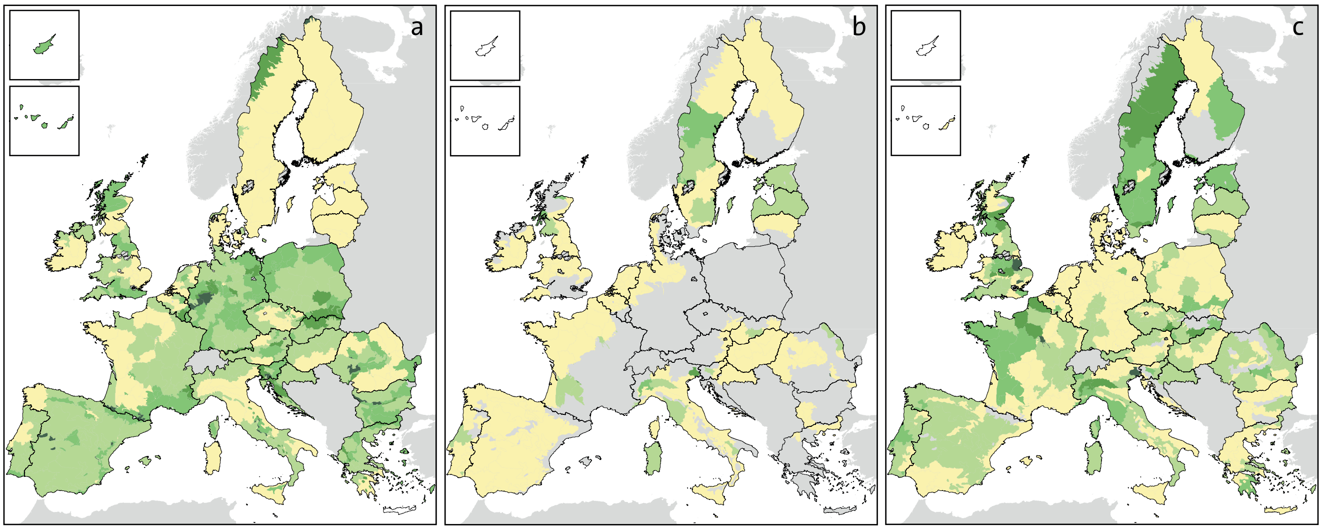
Evaluating and systematically improving the European Union’s nature protection network towards current and potential ecoregion representation targets



Current protected (a) and required additional protection area to reach 30% (b) or 50% (c) ecoregion coverage

< 20 % 40 - 60 % 80 - 100 % 20 - 40 % 60 - 80 % missing data

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Hamburg 2020

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Summary

In October 2020, the signatories of the Convention on Biological Diversity (CBD) need to adopt a new global strategy for biodiversity protection. With biodiversity loss ongoing, scientists demand ambitious targets for the CBD's post-2020 biodiversity strategy. Simultaneously, the European Union's (EU's) national biodiversity strategy runs out in 2020. Policymakers need assessments of the progress towards the current biodiversity strategy but also scenarios investigating the implications of potential post-2020 targets for well-informed decision-making. The aim of this thesis was therefore to develop a framework for evaluating and improving the ecological representation of the EU's protected area (PA) network based on systematic conservation planning principles. This framework was applied in two studies: First, to evaluate the Natura 2000 network's progress towards Aichi Target 11, which signatory parties to the CBD should accomplish until 2020. Second, to explore three scenarios illustrating how the EU could expand its PA network systematically to achieve potential higher 30% or 50% ecoregion coverage targets. The presented framework is the first that enables the evaluation and improvement of non-species biodiversity surrogates' representation for the EU's full PA extent including all 28 member states. It provides a gap analysis based on recently developed representation metrics and introduces a linear programming modeling system to simulate cost-efficient network expansion. The first study revealed that the coverage of six ecoregions falls short of the 10% representation target defined by the technical rationale to Aichi Target 11. 15 187 km² (0.35% of the European Union's land territory) would be required to close these existing coverage gaps. The second study showed that to realize 30% and 50% ecoregion coverage, the EU would need to add 6.6% and 24.2% of its terrestrial area to its PA network, respectively. For all three scenarios, the EU could designate most recommended new PAs in semi- or natural ecosystems. However, some ecoregions did not have enough natural areas left to implement the ecoregion coverage targets. Therefore, some member states would also need to establish new PAs on productive land. Overall, the results of the first study show that the Natura 2000 network might be the world's largest PA network, but it is still not ecologically representative and should therefore not be considered complete. The findings of the second study illustrate that more than half of all European ecoregions already reach 30% PA coverage and the remaining gap towards fully achieving that goal could be closed in the majority of ecoregions by protecting the remaining semi- or natural area. However, much greater effort would be needed to implement the Half-Earth vision in the EU. Both studies offer valuable information for the EU's post-2020 biodiversity strategy debate and can support discussions on the future of European biodiversity conservation.

Zusammenfassung

Die aktuelle Strategie der Biodiversitätskonvention läuft im Jahr 2020 aus, ohne dass der weltweite Biodiversitätsverlust bislang gestoppt werden konnte. Wissenschaftler fordern nun deutlich ambitioniertere Schutzziele für die neu zu verhandelnde Strategie der nächsten Dekade. Gleichzeitig muss die Europäische Union (EU) eine neue Biodiversitätsstrategie formulieren. Um dazu gute Entscheidungen auf politischer Ebene treffen zu können braucht es fundiertes Wissen zum Umsetzungsstand der aktuellen Schutzziele und Szenarien, die die Auswirkungen potentieller neuer Schutzziele evaluieren. Ziel dieser Thesis war es, das europäische Naturschutzgebietsnetzwerk hinsichtlich seiner ökologischen Repräsentanz zu evaluieren und aufzuzeigen, wie gegebenenfalls vorhandene Schutzlücken basierend auf Prinzipien der systematischen Naturschutzplanung geschlossen werden könnten. Dazu wurden zwei Studien verfasst. Für die erste Studie wurde untersucht, ob das Natura 2000 Netzwerk der EU ökologisch repräsentativ im Sinne von Aichi Ziel 11 der aktuellen Strategie der Biodiversitätskonvention ist. Die zweite Studie zeigt mit drei verschiedenen Szenarien auf, wie das gesamte Schutzgebietsnetzwerk der EU systematisch erweitert werden könnte um deutlich ambitioniertere 30% oder 50% Schutzziele für jede Ökoregion in der EU umzusetzen. Die Methodik, die beiden Studien zugrunde liegt, ermöglicht es, das gesamte Schutzgebietsnetzwerk aller 28 EU-Mitgliedsstaaten hinsichtlich des Schutzstatus von Ökoregionen und Habitaten zu evaluieren. Dazu werden kürzlich entwickelte Repräsentanz-Maßzahlen verwendet, um noch vorhandene Schutzlücken aufzuzeigen. Um diese Lücken möglichst systematisch und kosteneffizient zu schließen, wurde zudem ein auf linearer Optimierung basierendes Modellsystem entwickelt. Die Ergebnisse der ersten Studie zeigen, dass das Natura 2000 Netzwerk von sechs europäischen Ökoregionen weniger als 10% schützt und damit nicht das Schutzniveau realisiert hat, dass notwendig wäre, damit es als ökologisch repräsentativ im Sinne von Aichi Ziel 11 gelten kann. Um diese Lücke zu schließen müsste die EU auf zusätzlich 15 187 km² (0.35% der Landfläche der EU) neue Schutzgebiete ausweisen. Die zweite Studie zeigt auf, dass die EU noch 6.6% ihrer Landfläche schützen müsste um das 30% Schutzziel für alle Ökoregionen zu verwirklichen und 24.2%, wenn das 50% Schutzziel realisiert werden sollte. Für alle getesteten Szenarien könnten die Schutzziele in den meisten Ökoregionen durch das Unterschutzstellen von naturnahen Flächen erreicht werden. In manchen Ökoregionen ist jedoch nicht mehr ausreichend naturnahe Fläche vorhanden. Dort müssten Mitgliedsstaaten auch intensiv land- und forstwirtschaftlich genutzte Flächen extensivieren um Schutzziele zu erreichen. Die Ergebnisse der ersten Studie zeigen, dass das Natura 2000 Netzwerk, obwohl es das weltweit größte Naturschutznetzwerk ist, nicht ökologisch repräsentativ ist und daher nicht als fertiggestellt betrachtet werden sollte. EU Mitgliedsstaaten sollten vielmehr weiter daran arbeiten noch vorhandene Schutzlücken zu schließen. Wie die zweite Studie zeigt, hat mehr als die Hälfte der europäischen Ökoregionen das 30% Schutzziel bereits erreicht und die noch

vorhandenen Lücken könnten in fast allen Ökoregionen durch den zusätzlichen Schutz naturnaher Flächen geschlossen werden. Deutlich größere Anstrengungen müssten unternommen werden um die „Half-Earth“ Vision in der EU umzusetzen. Die Ergebnisse beider Studien können die Debatte um mögliche Ziele für die neue Biodiversitätsstrategie der EU nach 2020 unterstützen und Diskussionen über die Zukunft des Biodiversitätsschutzes innerhalb der EU anregen.

Publications related to this dissertation

Müller A., Schneider, U.A., Jantke, K. (2018). Is large good enough? Evaluating and improving representation of ecoregions and habitat types in the European Union's protected area network Natura 2000*,* Biological Conservation, 227, 292-300. DOI: 10.1016/j.biocon.2018.09.024

Contributions: A.M. designed the research with guidance from K.J.. A.M. and U.S. designed and performed the analysis. A.M. wrote the manuscript. K.J. and U.S. contributed to the discussion of the results and the manuscript at all stages.

Müller A., Schneider, U.A., Jantke, K. (2020). Evaluating and expanding the European Union's protected-area network toward potential post-2020 coverage target*s,* Conservation Biology. DOI: 10.1111/cobi.13479

Contributions: A.M. designed the research; A.M. designed the analysis with guidance from U.S.. A.M. performed the analysis and wrote the manuscript. K.J. and U.S. contributed to the discussion of the results and the manuscript at all stages.

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Abbreviations

CBD	*Convention on Biological Diversity*
CITES	*Convention on International Trade in Endangered Species*
COP 15	*15th Conference of the Parties*
CORINE	*Coordination of Information on the Environment*
EU	*European Union*
EUNIS	*European Nature Information System*
GAMS	*General Algebraic Modeling System*
GDP	*Gross domestic product*
GIS	*Geographic Information System*
IPBES	*Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*
IUCN	*International Union for Conservation of Nature*
MA	*Millennium Ecosystem Assessment*
MTA	*Mean target achievement metric*
NCP	*Nature's contributions to people*
NUTS	*Nomenclature of Territorial Units for Statistics*
PA	*Protected area*
PAME	*Protected area management effectiveness*
PE	*Protection equality metric*
SAR	*Species-area relationship*
SDG	*Sustainable development goal*
UN	*United Nations*
UNEP	*United Nations Environment Programme*
UNESCO	*United Nations Educational, Scientific and Cultural Organization*
WCMC	*World Conservation Monitoring Centre*
WDPA	*World Database of Protected Areas*

Unifying Essay

1. Setting the scene: Biodiversity loss and conservation efforts

1.1 Life on Earth is facing a human-caused sixth mass extinction event

The term biological diversity, often shortened to biodiversity, describes the variety of the living world. It encompasses the diversity of all organisms from the six kingdoms: archaebacteria, eubacteria, fungi, protists, plants, and animals. However, the concept of biodiversity is not restricted to the diversity of species alone but also comprises the diversity among genes and ecosystems (Swingland 2001). As fossil records show, today's biodiversity has evolved over millions of years through evolutionary processes. However, these fossil records do not only show the diversification of life but also reveal five big mass extinction events during which Earth lost more than three-quarters of the species extant at these times (Benton 1995). The causes of these past mass extinction events are still debated, but they were likely all driven by massive changes in abiotic conditions within the earth system (McElwain & Punyasena 2007).

In recent decades, a growing body of evidence suggests that Earth faces a sixth mass extinction event (Barnosky et al. 2011). De Vos et al. (2015) estimate current species extinction rates to be 1000 times higher than the natural background rate of extinction which might rise to a 10000 times higher rate in the future. Of the 112,432 species that the International Union for Conservation of Nature (IUCN) has assessed from 1964 to date, 27% are threatened with extinction, 6% are critically endangered and 1% are already extinct (IUCN 2019). These assessments show only the tip of the iceberg, the number of current species is still unknown. A recent estimation suggests that at least 1 billion and up to 6 billion species live on Earth today, of which only approximately 1.5 million species have been scientifically described (Larsen et al. 2017). Biodiversity loss manifests not only in global species extinctions but also in local species' population declines and extinctions. 8,851 of 27,600 land vertebrate species show population declines and local population losses, affecting 30% and more of the mammal, bird and reptile species, 15% of the amphibian species, and even species that are not classified as threatened by global extinction (Ceballos et al. 2017). The living planet index, which tracks the population abundances of 16,700 vertebrate species, has declined by 60% between 1970 and 2014. The most pronounced declines happened in the Neotropics, where vertebrate population sizes shrunk overall by 89%, and for freshwater ecosystems, where an 83% drop in population sizes was measured (WWF 2018). At the same time, the global assessment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) revealed that 75% of the land and 66% of the ocean area are nowadays significantly altered by human actions (IPBES 2019). Humanity has also altered biomass proportions on Earth since the beginning of civilization. The biomass of wild mammals has decreased sixfold while the total plant biomass has declined twofold. Today, the biomass of humans (approx. 0.06

Gigatonnes (Gt) carbon (C)) and livestock (approx. 0.1 Gt C) surpass the biomass of all wild mammals (approx. 0.007 Gt C) by far (Bar-On et al. 2018).

Reviewing existing scientific literature on current biodiversity loss, the IPBES global assessment affirmed that the current extinction event is human-made. It identified land and sea use change, unsustainable direct exploitation of organisms, climate change, pollution and invasion through alien species as the severest direct drivers of the observed changes in the natural world (IPBES 2019). However, the main underlying causes or indirect drivers are massive increases in the human population and the increases in global production, consumption, and trade. These drivers amplified the demand for energy and materials, especially during the last 50 years (Steffen et al. 2007; IPBES 2019).

1.2 The depletion of ecosystem services threatens human well-being

There are two complementary ethical viewpoints as to why humanity should care about the protection of biological diversity. The first one, called biocentrism, acknowledges that also non-human entities possess an intrinsic value. Based on this intrinsic value, biodiversity is entitled to moral considerations in its own right. Humans, therefore, have no right to exterminate other species (Mathews 2016). In contrast, the anthropocentric perspective views non-human entities only in terms of their utility for human purposes. However, even under such a utilitarian worldview, biodiversity research provides a rationale for the conservation of biological diversity, as societal and economic systems are inextricably linked to goods and services provided by the natural world. The Millennium Ecosystem Assessment (MA) illustrated the link between biodiversity, the functioning of healthy ecosystems and the goods and services such ecosystems provide that ultimately enable human well-being (Millennium Ecosystem Assessment 2005). The loss of biodiversity impairs the functioning of ecosystems and therefore their ability to provide what the MA termed “supporting ecosystems services”, e.g., nutrient cycling or primary production (Díaz et al. 2006; Tilman et al. 2014). This depletion of basic ecosystem functions decreases the ecosystems’ abilities to provide further provisional (e.g. food, freshwater), regulating (e.g. flood regulation, disease regulation) and cultural (e.g. spiritual or recreational) ecosystem services that are key to human well-being (Millennium Ecosystem Assessment 2005). The IPBES assessments have adopted this framework, using the term “nature’s contributions to people (NCP)” instead of “ecosystem services”. The global assessment reaffirmed the MA’s finding that most NCPs keep declining at global, regional and local scales (IPBES 2019).

To date, nine so-called planetary boundaries that humanity should not transgress to keep the earth system in the Holocene state to which human civilizations are adapted have been identified. Biodiversity loss is one of these nine boundaries (Rockström et al. 2009). In an updated version of the concept, Steffen et al. (2015) even point out climate change and biosphere integrity as the two core planetary boundaries. Notably, their indicator measures show that both boundaries have already reached the zone of uncertainty where risks for irreversible changes to the earth system increase.

One explanation why human-induced biodiversity loss continues even though our societies and economies crucially depend on a well-functioning natural world lies in the functioning of the market-based economy: All economic production processes require raw materials and generate waste outputs, creating the direct drivers that cause biodiversity loss. Economists call the associated depletion of ecosystem services a negative externality of production processes. It creates a welfare loss for society, for which the perpetrator does not need to pay any compensation. Therefore, producers have no sufficient incentive to consider these impacts when deciding whether to pursue the production activity and end up producing more than would be optimal from the society's perspective. This happens because many ecosystem services (at least the supporting, regulating and cultural) are public goods that do not show all necessary characteristics required to establish monetary values (prices) that would ensure effective allocation through a market.
(Daly & Farley 2004)

To stop biodiversity loss or at least preserve a level of biodiversity that maintains future flows of ecosystem services, governments need to correct this market failure through adequate policies (Kumar 2012).

1.3 Global efforts to protect biodiversity

Policymakers realized at the beginning of the 20th century that biodiversity loss was accelerating, which stimulated first multilateral agreements on the protection of certain species and the establishment of institutions such as the International Union for the Protection of Nature in 1948 (Arjjumend et al. 2016). The Convention on Wetlands (the Ramsar Convention) and the UNESCO's Man and Biosphere Program were both established in 1971, followed by the Convention for the Protection of the World Cultural and Natural Heritage in 1972. These were swiftly complemented in 1973 by the Convention on International Trade in Endangered Species (CITES) and in 1979 by the Convention on Migratory Species (the CMS, or Bonn Convention) (Pritchard 2005). Another milestone was reached in 1992 when the Convention on Biological Diversity (CBD, (Conference of the parties to the Convention on Biological Diversity 1992)) was opened for signature on the "Earth Summit" in Rio, entering into force in 1993 (Arjjumend et al. 2016).

To implement the goals of the convention, signatories to the CBD decided in 2001 to adopt a first strategic plan running from 2002-2010. When this first strategic plan failed to achieve a significant reduction of biodiversity loss by 2010, signatories adopted a second strategic plan running from 2011 until 2020 (Butchart et al. 2016). This strategy contains the vision of "living in harmony with nature" by 2050, which means that by then, "biodiversity is valued, conserved, restored and wisely used, maintaining ecosystem services, sustaining a healthy planet and delivering benefits essential for all people." (Conference of the parties to the CBD 2010). To facilitate the achievement of this vision, this second strategic plan contains 20 so-called Aichi targets that signatories to the CBD should meet until 2020. Besides, the United Nations (UN) declared 2011-2020 the decade on biodiversity. Acknowledging that a sustainable use of natural resources is necessary to maintain social and economic development, the UN Agenda for Sustainable Development until 2030 incorporates the protection of biodiversity explicitly in the sustainable development goals (SDGs) 14 (life below water) and 15 (life on land) (UNEP-WCMC et al. 2018).

1.4 Protected areas and conservation targets

One of the oldest, as well as most adaptable and diverse, measures to implement biodiversity protection on the ground is the designation of protected areas (PAs) (Woodley et al. 2012). The main objective of PAs is to eliminate or reduce pressures from direct human drivers of biodiversity loss, such as exploitation of organisms or land use change, within their boundaries (Schulze et al. 2018). A question for conservation practitioners and policymakers is how much area to include under such a protection regime, either to save a population at the local level or to stop biodiversity loss at the global level. At the local scale, ecological research examined the required habitat patch size to sustain a viable population. This threshold varies among species depending on the reproductive and dispersal attributes of each species (Fahrig 2001). A basic law in ecology, also known as the species-area relationship (SAR), states that larger areas contain more biodiversity. Researchers can estimate SAR to predict species extinctions from any on-going habitat loss (Smith 2010; Halley et al. 2013). However, estimates of SAR depend on input data quality (Metcalfe et al. 2013) and the functional form that is chosen to represent the SAR (Smith 2010), leading to a wide range in habitat conservation target estimates. Deriving a unique science-based global PA target similar to the 2° target from the Paris Agreement to limit climate change has not yet been possible (Sleep et al. 2017). During the last decades, nations adopted a sequence of increasing but arbitrarily set global conservation targets created through political negotiations.

In 1987, the Brundtland Report (World Commission on Environment and Development 1987) concluded that only three to four percent of the global land area was protected and suggested that the global PA extent should at least be tripled to conserve a representative sample of Earth's ecosystems (Locke 2013). Even though conservation experts judged the protection of 10% or 12% of the global land area as insufficient to prevent the further loss of biodiversity, they deemed higher targets politically infeasible at that time (Soule & Sanjayan 1998). During the negotiations for the CBD's 2011-2020 strategic plan on biodiversity, signatories agreed to a slightly raised target. Aichi Target 11 calls for the protection of "at least 17 percent of terrestrial and inland water, and 10 percent of coastal and marine areas, […] conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas […]" until 2020 (Conference of the parties to the Convention on Biological Diversity 2010). Again, ecologists pointed out that the 17%/10% target is a politically negotiated compromise with no scientific evidence proving it sufficiently high to stop biodiversity loss (Maxwell et al. 2015; Woinarski 2016). Targets derived from empirical data, models, prioritization algorithms, reviews, and expert opinion usually exceed political conservation targets (Noss et al. 2012). According to Noss and Cooperrider (1994), protection levels could vary between regions but should range between 25% and 75% to sustain biodiversity and ecological processes. One of the founders of the Half-Earth movement calls for the protection of 50% of the planet to conserve 85% of all species (Wilson 2016). Similarly, Baillie and Zhang (2018) suggest protecting 30% until 2030 and 50% until 2050. While the recommendations vary considerably, they all fall well above the currently envisaged 17%/10% protection. Notably, the zero draft of the CBD's post-2020 global biodiversity framework calls for the protection for 30% of the land and sea area until 2030 (Working group on the post-2020 global biodiversity framework 2020). If signatories to the CBD choose to adopt this draft, they will decide on a much bolder conservation target for the next decade.

Although past global conservation targets were set arbitrarily, they helped increase the global terrestrial PA estate from roughly 3.5% in 1985 (Zimmerer et al. 2004) to 14.9% in 2018 (UNEP-WCMC et al. 2018). Similarly, the global marine PA estate increased from about 0.8% in national waters in 1982 (Jantke, Jones, et al. 2018) to 18.5% in 2020 (UNEP-WCMC and IUCN 2020). Research verified that PAs reduce the conversion rate of natural land cover (Joppa & Pfaff 2011), halt net habitat loss (Biró et al. 2018) and enable the persistence of forests (Geldmann et al. 2013). The existing literature shows mixed evidence on the ability of PAs to maintain species populations compared to non-protected areas but the larger share of studies support this hypothesis, especially on the global scale (Geldmann et al. 2013; Coetzee et al. 2014; Barnes et al. 2016; Gray et al. 2016). Furthermore, while global climate change will likely change the distribution patterns of ecosystems and their associated species (Jennings & Harris 2017), PAs might reduce the extinction risk of species affected by these climatic changes and facilitate the colonization of new suitable habitat area (Peach et al. 2019).

While the global PA estate is growing, human needs expand further as well, often leading to conflicts between biodiversity protection and other competing land uses (McIntosh et al. 2017). Although nations establish more PA globally, many local PAs are downsized, degazetted or their protection regime is downgraded, usually to allow for the exploitation of natural resources or to facilitate recreational activities (Woodley et al. 2012; Schulze et al. 2018). Additionally, insufficient funding, lacking enforcement and inadequate management reduce the effectiveness of many PAs to "paper parks" that create no benefit for biodiversity protection on the ground (Barnes et al. 2018; Geldmann et al. 2019). Globally, one-third of protected land is still under intense human pressure and might therefore not be able to provide the habitat quality necessary to preserve local biodiversity (Jones et al. 2018). Many countries, while aiming to raise their protection levels, seek to avoid tradeoffs with competing land uses. PA designations are thus specifically located in areas least suitable for other uses, while the biodiversity of productive, easily accessible landscapes often remains unprotected (Pressey et al. 2002). An evaluation of 147 national PA networks showed that PA designation often occurred in higher elevations, steeper slopes and far away from roads and cities, i.e., places that already had a low risk of land conversion and therefore were in the least need of protection (Joppa & Pfaff 2009). Therefore, biodiversity protection relies crucially on the effective planning and implementation of reserve networks. As a response to this need, systematic conservation planning emerged as a sub-discipline of conservation biology, offering a scientific framework and planning principles to ensure higher effectiveness of PA networks (Watson et al. 2011).

2. Systematic conservation planning – a scientific discipline to increase protected area effectiveness

2.1 The three basic principles of systematic conservation planning

Systematic conservation planning relies on three basic objectives to design reserve networks that protect biodiversity effectively. The first objective is representativeness. Ideally, a PA network should sample the full variety of biodiversity that exists in the respective planning region on all levels of organization. The second objective is persistence. Reserve networks should ensure the long-term survival of biodiversity by maintaining natural processes and viable species populations and by excluding direct drivers of biodiversity loss (Margules & Pressey 2000; Margules & Sarkar 2007). Finally, efficient use of resources while achieving the two previous objectives has been added since as a third basic goal (Sarkar & Illoldi-Rangel 2010). In addition to these three core principles, Kukkala and Moilanen (2013) found and reviewed 12 concepts of spatial prioritization and systematic conservation planning, of which some will be mentioned below. Initially, Margules and Pressey (2000) proposed a six-stage framework for the planning and implementation of PA networks that would fulfill the core principles. Later, this framework was updated to 13 stages (Sarkar & Illoldi-Rangel 2010); however, the six original stages suffice to describe the general idea of the framework.

2.2 The six stages of the systematic conservation planning framework

The first stage is the inventory of the biodiversity found within a planning region. Unfortunately, distribution data for all existing biodiversity entities is not available for any region in the world. Therefore, choosing a biodiversity surrogate is necessary. Usually, a subset of species is selected, but this approach has two limitations. First, the surrogate effectiveness of well-known species or taxa remains debated (Rodrigues & Brooks 2007). Second, even for such a subsample of biodiversity, it is difficult to collect complete fine-scale distributional data and keep it up to date (Sarkar et al. 2006). Nevertheless, species-based biodiversity evaluations were carried out on the global (Rodrigues et al. 2004), national (Fajardo et al. 2014; Lessmann et al. 2014; Quan et al.

2018) and regional scale (Pearce et al. 2008; Cabeza et al. 2010). Other surrogates such as potential natural vegetation (Rosati et al. 2008) or ecosystems (Franklin 1993; Dietz & Czech 2005) have also been tested, as distribution data for these might be easier collected (Bunce et al. 2013) or modeled (Mücher et al. 2009). Some evaluations have included both, ecosystems and threatened species (Polak et al. 2015) or even species ranges, ecosystem types and forest carbon stocks at the same time (Williams et al. 2019).

The second stage is the determination of explicit quantitative conservation targets (Margules & Pressey 2000). This stage is closely linked to the concept of adequacy (Kukkala & Moilanen 2013), dealing with how much to protect each biodiversity entity to ensure its persistence. The choice of such conservation targets directly influences the outcome of a systematic conservation planning exercise (Vimal et al. 2011). For species, a range of targets have been applied from single (Rodrigues et al. 2004; Araújo et al. 2007) and multiple representations of a species' mapped distribution (Bonn & Gaston 2005; Abellán & Sánchez-Fernández 2015) to a minimum required coverage (Diserens et al. 2017) or the representation of one or several viable populations (Jantke et al. 2011). These targets can be uniform targets for all included species or species-specific targets, e.g. based on species' range sizes (Maiorano et al. 2015). For habitats or ecosystems, scientists usually adopt percentage coverage targets based on the SAR rationale that the preservation of a certain amount of habitat would allow the continued existence of a certain number of its associated species. Again, the easiest option is to use a uniform target and ensure equal protection across all habitat types or ecosystems. Rondinini and Chiozza (2010) reviewed a range of methods that enable the estimation of habitat-specific targets but found none of the methods they assessed ideal. Inadequate targets could lead to unnecessary costs for society in case of overestimation and continued loss of biodiversity in case of underestimation (Smith et al. 2006; Carwardine et al. 2009; Moilanen et al. 2009). However, the benefits of tangible percentage targets are measurability and simplicity that make them easy to track and explain (Carwardine et al. 2009) and thereby help to enhance local biodiversity protection.

The third stage is the evaluation of the existing PA network (Margules & Pressey 2000). As most nations on Earth have designated PAs in their terrestrial area and national waters already (UNEP-WCMC and IUCN 2019), systematic conservation planning exercises usually do not start from zero but aim at increasing the effectiveness of existing networks. Traditionally, a reserve network is considered effective if all biodiversity surrogates defined in the first stage reach the level of ecological representation defined by the targets set in stage two (Kukkala & Moilanen 2013). If this is not the case, then so-called conservation gaps remain that need to be closed to achieve a higher PA network effectiveness. GIS-based spatial overlay methods for conducting such gap analyses are well-established (Scott et al. 1993; Jennings 2000), but the introduction of representation metrics further refined this approach in recent years. Representation metrics offer transparency, an easy-to-understand percentage output to track progress towards achieving ecological representation over time and an option for comparing the ecological representation of different reserve networks (Barr et al. 2011; Sutcliffe et al. 2015; Chauvenet et al. 2017; Jantke, Kuempel, et al. 2018). Besides ecological representation, connectivity among PAs is a network design factor enabling the persistence of biodiversity for which indicators have been developed and applied (Saura & Pascual-Hortal 2007; Saura et al. 2017).

The fourth stage of the framework is an expansion plan for the existing PA network that closes biodiversity surrogates' coverage gaps at minimum cost (Margules & Pressey 2000). Cocks and Baird (1989) first formulated this problem mathematically as the so-called minimum set problem. Closely related is the maximal coverage conservation prioritization problem, which is usually applied when there are insufficient funds to achieve adequate representation of all biodiversity surrogates. The goal of this approach is to satisfy the largest number of representation and/or persistence targets with a fixed conservation budget (Watson et al. 2011). Ideally, the cost data include both forgone opportunity costs and direct costs such as acquisition or management costs (Naidoo et al. 2006). Land rental rates can serve as a proxy for opportunity costs and are the most readily available data (Ando et al. 1998; Jantke et al. 2016). While national studies that include both opportunity costs and direct costs exist (Petersen et al. 2016), the direct costs of conservation are often not available and difficult to estimate (Kotiaho & Moilanen 2015).

A few open-source software packages solve spatial prioritization problems using heuristic algorithms that only approximate the optimal solution (Moilanen et al. 2009). One well-known software tool is Marxan, which solves the minimum set problem using simulated annealing (Watts et al. 2009). Another established software package, Zonation, also uses heuristic algorithms but does not solve a minimum set problem. Instead, it provides a conservation priority ranking for the entire landscape (Moilanen et al. 2005). In contrast to heuristic algorithms, standard optimization algorithms calculate an optimal solution to the minimum set problem. In the past, computation times to solve very large problems were so high that these algorithms were outcompeted by heuristic algorithms in terms of computational efficiency (Possingham et al. 2000). However, there are examples of successful applications of integer programming to solve spatial prioritization problems (Stralberg et al. 2009; Jantke & Schneider 2010) and integer linear programming algorithms provide verifiable solution qualities (Beyer et al. 2016).

The fifth stage is the implementation of conservation action on the ground (Margules & Pressey 2000). There are examples of successfully implemented systematic conservation planning exercises such as the rezoning of the Great Barrier Reef Marine Park, Australia (Fernandes et al. 2005), the expansion of the PA network in Northern Zululand, South Africa (Maddock & Benn 2000), or minimizing ecological impacts of peat mining for a region in Central Finland (Kareksela et al. 2018). Nevertheless, most conservation assessments published in peer-reviewed literature do end with stage four and never enter the implementation phase, mostly because researchers never planned for an implementation (Knight et al. 2008). Researchers described this phenomenon as a research-implementation or an assessment-implementation gap (Adams et al. 2019) and a comprehensive review of more than 10,000 articles found only a tiny fraction (n=43) of systematic conservation planning exercises reporting outcomes of interventions (McIntosh et al. 2018). However, Sinclair et al. (2018) surveyed authors of spatial conservation prioritizations and identified two types of spatial prioritization exercises, i.e., those that are solely designed to advance the field (n= 69) and those that are intended for implementation (n=96). They found that 74% of the prioritization exercises intended for implementation led to on-ground actions.

The sixth and last stage is the management and monitoring of PA networks (Margules & Pressey 2000). As the global PA estate was continuously increasing during past decades, researchers developed indicators to assess the management effectiveness within existing reserve networks. The human footprint index visualizes the large-scale management effectiveness of reserve networks (Sanderson et al. 2002; Venter et al. 2016; Jones et al. 2018). Additionally, PA management effectiveness (PAME) tools have been developed for local and regional more in-depth assessments (Coad et al. 2015; Moreaux et al. 2018).

2.3 Evaluation of progress towards global conservation targets based on systematic conservation planning methods

As the Convention on Biological Diversity's second strategic plan on biodiversity and its Aichi targets expire in 2020, systematic conservation planning principles have been used to assess progress towards Aichi Target 11 that especially deals with PAs. However, most studies only conducted gap analyses and did not simulate cost-efficient expansion to close remaining gaps. On a global scale, Tittensor et al. (2014) used nine indicators to evaluate progress towards Aichi Target 11. Besides the total PA extent, they also evaluated how many terrestrial and freshwater ecoregions reached 17% protection and how many marine ecoregions reached 10% protection. Another global gap analysis tested ecoregion representation towards a 17% representation target (Watson et al. 2016). A recent global assessment of Aichi Target 11 uses the mean target achievement metric (Jantke, Kuempel, et al. 2018) to evaluate the ecological representation of ecoregions towards 2%, 10% or 17% coverage targets, respectively (Gannon et al. 2019). Two global analyses used systematic conservation software to identify priority regions for network expansion to meet Aichi Target 11. Butchart et al. (2015) evaluated progress towards Aichi Target 11 by analyzing total PA coverage, but also PA coverage for many biodiversity surrogates, e.g. ecoregions, biomes, important sites for biodiversity and species' distribution ranges. They found that only a small amount of additional conservation areas would need to be added to the global PA extent to achieve the 17% coverage target. However, realizing an adequate representation for all biodiversity surrogates would only be possible if the total terrestrial network extent would be raised to roughly 28%. Pouzols et al. (2014) simulated priority areas for network expansion to reach the 17% global PA coverage target while increasing the representation of vertebrate species and ecoregions as much as possible. For potential higher conservation targets, a global gap analysis was conducted for the Half-Earth vision, breaking it down to the protection of 50% of all ecoregions (Dinerstein et al. 2017a).

The implementation of any strategic plan the CBD's signatories agree upon depends on the national contributions of each signatory. Therefore, Aichi target 17 called for each signatory to submit a National Biodiversity Strategy and Action Plan until 2015 (Conference of the parties to the Convention on Biological Diversity 2010). A signatory-scale assessment evaluating national progress towards Aichi Target 11 and simulating network expansion to close coverage gaps has only been published in the scientific literature for Japan (Naoe et al. 2015). However, gap analyses for reaching Aichi Target 11 exist for Canada (MacKinnon et al. 2015; Hagerman & Pelai 2016), the Philippines (Mallari et al. 2016) and the European Union (Beresford et al. 2016).

3. Biodiversity protection efforts in the European Union

3.1 The EU's biodiversity strategy and protected area network

The European Union (EU) is one of the 193 signatories to the CBD and its National Biodiversity Strategy and Action Plan will expire in 2020 as will the CBD's global biodiversity strategy. The current EU biodiversity strategy contains six targets and 20 necessary actions to reach them (European Commission 2012). One of these actions is to finish the establishment of the Natura 2000 network. Natura 2000 is an EU-wide network of PAs designated for about 200 bird species listed on Annex I of the birds directive (The European Parliament and the Council of the European Union 2009), roughly 400 species listed on Annex II of the habitats directive and about 200 habitat types listed on Annex I of the habitats directive (The Council of the European Communities 1992). A mid-term review in 2015 revealed that Natura 2000 sites (Fig. 1) already covered 18.1% of the EU's land area, thereby fulfilling the 17% protection target of Aichi Target 11. The terrestrial part of the Natura 2000 network was therefore considered completed (European Commission 2015). While the marine Natura 2000 network still fell short of meeting the 10% target of Aichi Target 11 in 2015, it has reached 10% coverage to this date (European Environment Agency 2018). Currently, Natura 2000 is the world's largest coordinated nature protection network (Campagnaro et al. 2019). Considering also member states' nationally designated PAs that are not part of Natura 2000 (Fig. 1), more than 26.3% of the EU's terrestrial area is protected (UNEP-WCMC and IUCN 2019).

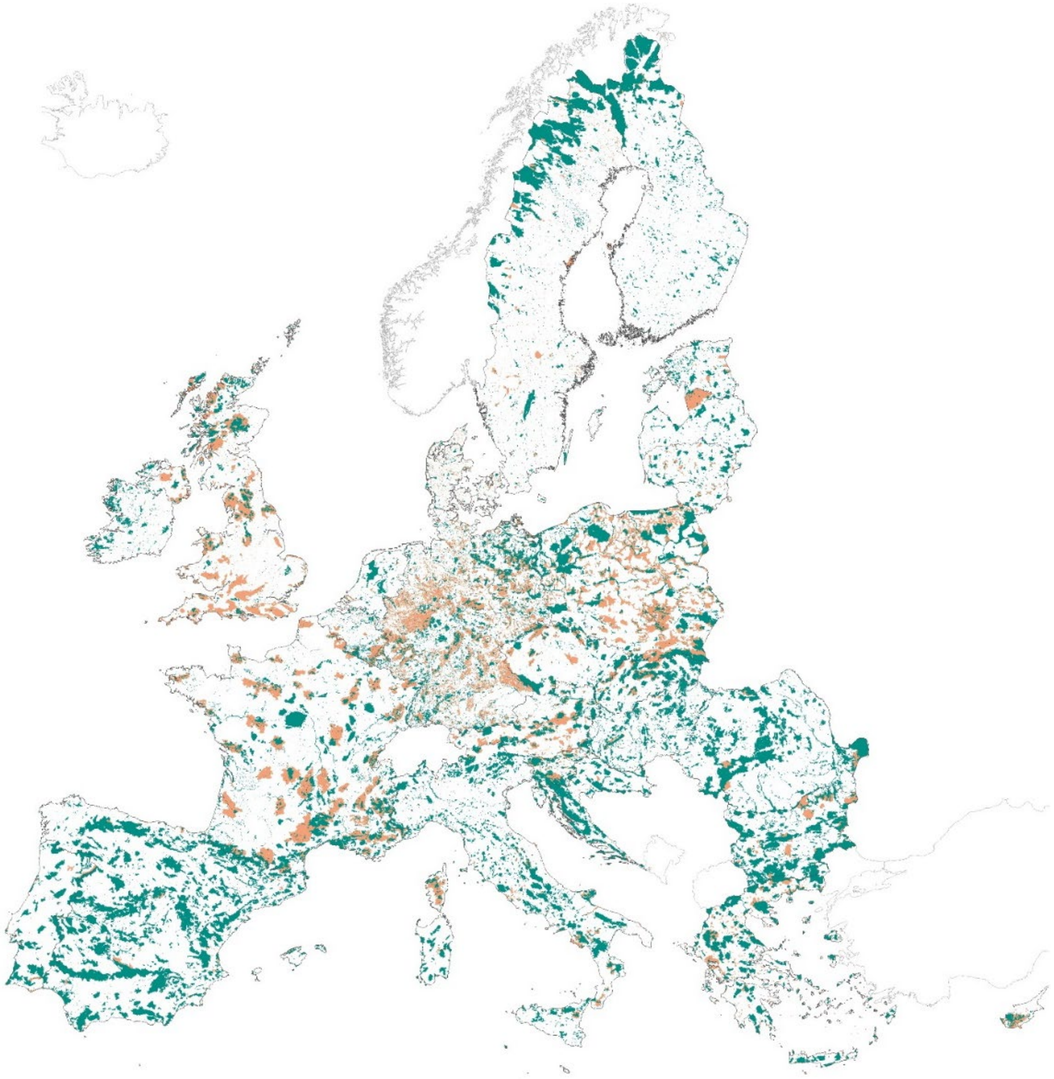

Figure 1 *The European Union's terrestrial Natura 2000 sites (green, Directorate-General for Environment (DG ENV) (2017)) and additional PA categories based on member states' national legislation (orange, UNEP-WCMC and IUCN (2019)). Map based on the datasets cited in the previous sentence with national borders taken from EuroGeographics (2013).*

3.2 Current status of European biodiversity

The recent IPBES regional assessment for Europe and Central Asia still finds overall negative status and trends for biodiversity in this region (IPBES 2018). Particularly, 22.7% of the 11,260 European species assessed on the IUCN Red List are still threatened by extinction (IUCN 2017). Furthermore, Article 12 of the birds directive and Article 17 of the habitats directive demand regular monitoring of the status and trends of species and habitat types listed on the annexes mentioned above, which is carried out for six-year periods. While the latest state of nature report based on the most recent reporting period from 2013-2018 is not published yet, a draft comparison to the data compiled for the 2007-2012 period is already available online. For the breeding populations of birds, the relative amount of populations that showa negative trend in the short term further increased from 23% in the 2007-2012 period to 26% in the 2013-2018 period (European Environment Agency 2019a). Similar, the number of habitat types with an unfavorable conservation status increased from 69% in the 2007-2012 period to 72% in the 2013-2018 period and the number of species with an unfavorable conservation status increased from 55% in the 2007-2012 period to 57% in the 2013-2018 period (European Environment Agency 2019b). This most recent update on the condition of the EU's biodiversity reveals that the Natura 2000 network, despite being large, is not effective in stopping biodiversity loss in Europe.

3.3 Previous research on biodiversity representation in the EU's reserve network

Based on systematic conservation planning theory, a PA network can only protect biodiversity effectively if it is fully representative. Previous studies assessing the representation of biodiversity in the reserve network of the European Union have been reviewed by Orlikowska et al. (2016) and Zisenis (2017). Notably, even though the Natura 2000 network is a pan-European network of PA, researchers carried out the majority of gap analyses on member state level (Maiorano et al. 2007; Rosati et al. 2008; Sánchez-Fernández et al. 2008; Hernández-Manrique et al. 2012; D'Amen et al. 2013; Mikkonen & Moilanen 2013; Rubio-Salcedo et al. 2013; Hermoso et al. 2015b; Petersen et al. 2016; Diserens et al. 2017; Friedrichs et al. 2018; Pechanec et al. 2018) or regional level (Dimitrakopoulos et al. 2004; Abellán et al. 2011; Lisón et al. 2013; Hermoso et al. 2015a; Duarte et al. 2016). Most of the studies carried out for the entire EU or European continent used species as biodiversity surrogates. Examples include species listed on Annex II of the habitats directive (Gruber et al. 2012), terrestrial vertebrates (Maiorano et al. 2015; Kukkala, Arponen, et al. 2016), birds (Kukkala, Santangeli, et al. 2016), amphibians and reptiles (Sánchez-Fernández & Abellán 2015), large carnivores (Santini et al. 2016), wetland vertebrates (Jantke et al. 2011), or threatened species (Trochet & Schmeller 2013). However, some studies evaluated the Natura 2000 network based on non-species surrogates, such as biogeographical regions (European Environment Agency 2012) or ecoregions (Beresford et al. 2016). While all studies mentioned above provide gap analyses to evaluate the coverage of biodiversity in the existing PA network extent, simulations yielding priority areas for network expansion to close existing representation gaps have rarely been conducted (but see Mikkonen & Moilanen 2013; Kukkala, Arponen, et al. 2016; Kukkala, Santangeli, et al. 2016; Diserens et al. 2017). Studies investigating cost-efficient enlargement of the Natura 2000 network are even scarcer (but see Jantke et al. 2011; Petersen et al. 2016).

Finally, the concern that protecting 17% of the global terrestrial land area will not be enough to stop the loss of biodiversity also applies to the European Union scale. The European Parliament recently published a resolution calling for "an ambitious and inclusive Biodiversity Strategy for 2030 that sets legally binding targets for the EU and its Member States, including specific targets to reach at least 30 % of protected terrestrial and marine areas"(European Parliament 2020). Additionally, the European Parliament "calls for the EU to push for an increased level of ambition […] and potentially call for protecting half of the planet by 2050" (European Parliament 2020).

However, the only gap analysis conducted to date for higher conservation targets was evaluating the achievement of the Half-Earth vision in each of the world's ecoregions (Dinerstein et al. 2017a).

4. A modeling framework for evaluating and improving ecological representation in the European Union's nature protection network

4.1 Aim of the thesis

In 2020, the European Union needs to formulate a new national biodiversity strategy. This European strategy will also be influenced by the CBD's post-2020 biodiversity strategy that signatories will adopt at the 15th Conference of the Parties (COP 15) to the CBD in Kunming, China. Policymakers need assessments of the progress towards the current biodiversity strategies (Conference of the parties to the Convention on Biological Diversity 2018a) but also scenarios that investigate the implications of potential post-2020 targets for well-informed decision-making (Conference of the parties to the Convention on Biological Diversity 2018b). The aim of this thesis was therefore to develop a framework for evaluating and improving the ecological representation of the EU's PA network based on systematic conservation planning principles. While the scientific literature contains a large number of studies evaluating biodiversity representation in the European context, only a minority was conducted for the entire EU. Furthermore, most studies focused on gap analyses for a sub-sample of species. While these studies provide insights on representation gaps for the respective species groups, they neglect further components of biodiversity, e.g., invertebrate or microscopic organisms, for which distribution data is not yet available (Hill et al. 2016). Additionally, gap analyses provide prerequisites for decision making in the conservation context but are not sufficient to deliver ecologically effective and cost-efficient conservation plans. Instead, any suggestion for network expansion should consider at least some economic, political or social constraints (Brown et al. 2015). The framework presented in this thesis remedies some of these existing gaps in the literature. It is the first framework that enables the evaluation and improvement of non-species biodiversity surrogates' representation for the EU's full PA extent including all 28 member states. To this end, it provides a gap analysis based on recently developed representation metrics and a cost-efficient simulation of network expansion founded on the best available EU-level proxy data for forgone opportunity cost.

4.2 Description of the modeling framework

The primary biodiversity surrogates for this framework are the ecoregions located within the EU's terrestrial territory (Fig. 2). Olson et al. (2001) published a first map of the ecoregions of the world and defined them as "large units of land containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land use change." (Olson et al. 2001). In contrast to many other biodiversity surrogates' distribution datasets, the recently revisited and updated map of ecoregions (Dinerstein et al. 2017b) offers comprehensive coverage of the whole world. Therefore, ecoregions have been frequently used to evaluate ecological representation on the global level (Woodley et al. 2012; Tittensor et al. 2014; Watson et al. 2016; Gannon et al. 2019) and the CBD adopted them as a measure of ecological representation, too (Convention on Biological Diversity 2013; Conference of the parties to the Convention on Biological Diversity 2018a).

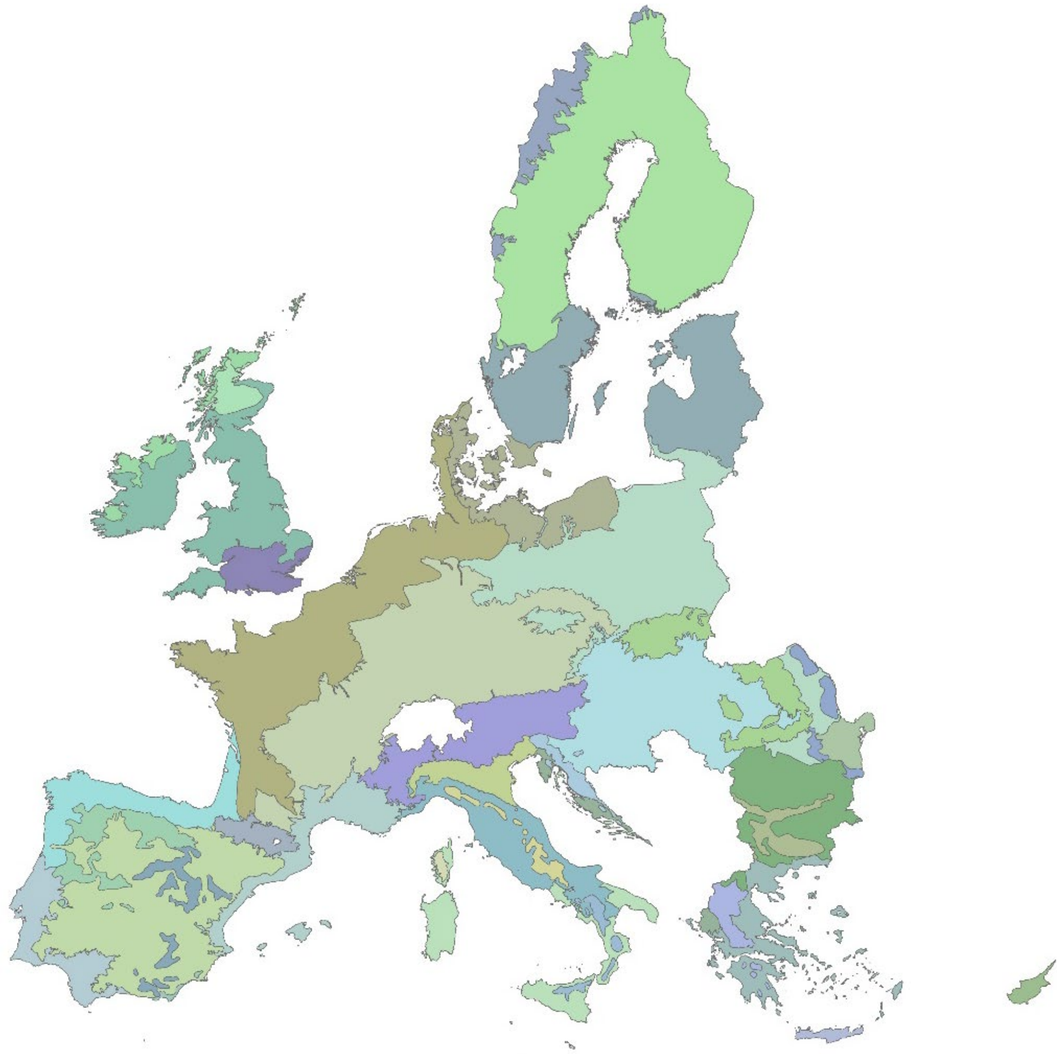

Figure 2 *The 41 ecoregions located within the terrestrial area of the EU. Map based on the Ecoregions RESOLVE dataset (Dinerstein et al. 2017b).*

However, one limitation of ecoregions as biodiversity surrogates is that most of them contain a variety of habitat types or ecosystems (Olson et al. 2001). For example, the European forest ecoregions, such as Western European broadleaf forests, do not only contain forest habitat types, but also peatlands, grasslands, and freshwater ecosystems. To address this limitation of the ecoregion dataset, habitat types and ecosystems respectively are included as a secondary biodiversity surrogate in the modeling framework.

Deciding on adequate representation targets for ecoregions is as difficult as it is for species' ranges. It is not yet known how much protection for each ecoregion is needed in order to enable the persistence of the characteristic biodiversity. Nevertheless, ecoregions have been used frequently to enable a more representative allocation of PAs designated to reach global conservation targets (Joppa & Pfaff 2009), e.g. for the 17% target (Butchart et al. 2015) or to reach the Half-Earth vision (Dinerstein et al. 2017a). For the modeling framework proposed in this thesis, a homogenous ecoregion coverage target was implemented. The mean target achievement (MTA) metric (Jantke, Kuempel, et al. 2018) was calculated to evaluate progress towards any given target for all ecoregions. No additional coverage target was set for the secondary biodiversity surrogate. Instead, habitat representation was evaluated with the protection equality (PE) metric (Chauvenet et al. 2017), which measures how homogeneously a PA network protects biodiversity features, such as habitat types.

Based on the choice of biodiversity surrogates, conservation targets and representation metrics, a minimum set planning problem that would allow simulating the cost-efficient expansion of the EU's reserve network was formulated. The main objective of that problem was to expand the EU's PA network to reach a given level of ecoregion representation. To refine the selection of additional PAs to sites most suitable for increasing biodiversity representation, the second objective was to improve habitat protection equality while closing ecoregion's representation gaps. Finally, both previous objectives should be achieved as cost-efficiently as possible. To solve this minimum set problem, a linear programming-based modeling system consisting of two consecutive optimization models was developed (Fig. 3).

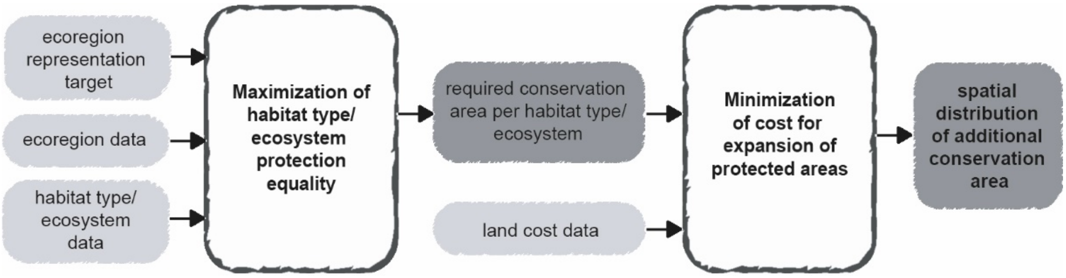

Figure 3 *Overview of the modeling approach. Light grey boxes depict input data, dark grey boxes output data and white boxes with dark fringes show analysis tools.*

The first optimization model closes ecoregions' representation gaps while simultaneously aligning the protected shares of habitats in the entire reserve network as much as possible. This ensures that habitats currently least represented in the PA network are prioritized for additional conservation areas if they occur within one of the gap ecoregions. The second optimization model allocates the required additional conservation area per habitat for each ecoregion to the cheapest set of planning regions based on land cost or land rent data as proxies for foregone opportunity cost. The modeling system was implemented in the modeling language GAMS (General

Algebraic Modeling System) and solved using the optimization algorithm CPLEX. Section I and II contain the model equations as well as a detailed model description.

4.3 Summary of the first study: Is large good enough? Evaluating and improving representation of ecoregions and habitat types in the European Union's protected area network Natura 2000

This cumulative thesis consists of two studies, both covering research that was conducted using the modeling framework. The goal of the first article was an evaluation of the Natura 2000 network's progress towards Aichi Target 11 that signatory parties to the CBD should accomplish until 2020. The terrestrial Natura 2000 network already transgresses the 17% coverage target. However, Aichi Target 11 also contains a clause demanding PAs to be "ecologically representative". The technical rationale to Aichi Target 11 defines a network as ecologically representative if it protects 10% of each ecoregion located within a signatory's territory (Conference of the parties to the CBD 2010). Therefore, the first study addresses the following three research questions:

1. Does the Natura 2000 network represent 10% of each European ecoregion?
2. How could the EU expand the Natura 2000 network cost-efficiently to reach the ecological representation component of Aichi Target 11?
3. How much could this expansion increase the representation of European Red List habitat types simultaneously?

The evaluation of the current Natura 2000 network extent revealed a mean target achievement of 96% as it currently underrepresents six ecoregions that did not meet the 10% coverage target (Fig. I.2). However, only one ecoregion, the Northern Italian Po basin mixed forests, still falls short of 10% representation if all PA categories reported to the World Database of Protected Areas (WDPA) were considered (Fig. 4). The EU could cost-efficiently expand the Natura 2000 network to achieve 10% ecoregion representation by adding about 15,200 km^2 to existing Natura 2000 sites. This equals only about 0.35% of the EU's land area (Fig. I.4). The majority of this additional PA would need to be designated within the United Kingdom, which did not designate many Natura 2000 sites in its territory despite a much larger network of nationally designated PA categories. In total, 11 out of the 28 EU member states would need to expand their national Natura 2000 networks (Fig. I.5A).

Figure 4 *Ecoregion coverage for 10%, 30% and 50% representation targets, respectively. Note how protected proportions for ecoregions change if only the Natura 2000 sites or all PA categories reported to the World Database on Protected Areas (WDPA) are included in the evaluation.*

For the 226 habitat types that served as secondary biodiversity surrogate in this study, protection levels within Natura 2000 ranged between 8% and 96%, resulting in 72% protection equality, which is a quite high metric output. Despite increasing the protection levels of 21 habitat types (Fig. I.5B), the simulated network expansion would only raise protection equality of habitat types to 73%. This is due to the formulation of the minimum set problem that mainly aims at achieving the ecoregion representation target. This procedure leaves the optimization algorithm with few degrees of freedom for the subordinate improvement of habitat types' protection equality. Overall, the results support the findings of previous gap analyses based on species as biodiversity surrogates: The terrestrial Natura 2000 network might be the world's largest, but it is still not ecologically representative and therefore the member states should keep adding sites to close remaining conservation gaps. Section I contains the full research article published in the journal Biological Conservation.

4.4 Summary of the second study: Evaluating and expanding the European Union's protected-area network toward potential post-2020 coverage targets

The CBD's current strategic plan on biodiversity and the EU's National Biodiversity Strategy both expire in 2020. The zero draft on the CBD's post-2020 biodiversity strategy suggests protecting 30% of the planet and the European Parliament is calling for the protection of 30% of the EU's terrestrial and marine areas until 2030. Furthermore, the non-governmental initiative *Nature-needs-half* has advocated setting aside half of the planet as PAs to solve the biodiversity crisis and European Parliament calls for the EU to advocate protecting 50% of the planet until 2050 at COP 15. Higher conservation targets in the international biodiversity strategy would probably also influence the EU's post-2020 national biodiversity strategy. However, the European Union is twice as densely populated as the world average and has a long history of human land use and habitat degradation (McCloskey & Spalding 1989). The goal of the research reported in the second study was, therefore, to explore how the European Union could expand its PA network systematically and cost-efficiently to achieve the potential higher protection targets. The linear programming modeling system described previously was refined to answer the following four research questions:

1. Which ecoregions within the EU's PA network already reach 30% or 50% representation?

2. Which ecoregions do not have enough natural area left to reach 30% or 50% representation?

3. How could the network be expanded cost-efficiently to reach 30% or 50% ecoregion representation?

4. How much productive forest and agricultural area would need to be restored to reach the respective target?

The EU's reserve network, consisting of Natura 2000 sites and other PA categories based on member states' national legislation, covers 30% of 26 ecoregions. This produces a mean target achievement of 88%. In nine ecoregions, the network covers at least 50%, with a mean target achievement of 68% (Fig. II.1 & Fig. 4). The gap towards 30% ecoregion representation is rather small and the EU would only need to add another 6.6% of its land area as additional PAs. Fully implementing 50% ecoregion representation would require a far larger increase of PA extent, adding roughly another quarter of the EU's terrestrial area. Three ecoregions do not have enough semi-natural or natural ecosystem areas left to enable 30% ecoregion representation. For the 50% ecoregion representation target, this is the case for 15 ecoregions (Fig. II.2B).

Respective representation targets could still be implemented in these ecoregions if EU member states would fill the remaining gaps by restoring highly productive forests and grasslands or arable land into states favorable for biodiversity protection.

For the cost-efficient network expansion, three minimum set problems were defined to compare three scenarios for potential network expansion. The 'ecosystem equity' scenario is the original minimum set problem using ecosystem classes from the CORINE land cover dataset as secondary biodiversity surrogate. The 'cost-only' scenario closes ecoregion representation gaps without considering a secondary biodiversity surrogate. Finally, the 'member state equity' scenario closes ecoregions' representation gaps while aligning member states' protected proportions as equally as possible. Unsurprisingly, 'cost only' delivered the cheapest network expansion, but the highest ecosystem protection equality was achieved by the 'ecosystem equity scenario' (raising protection equality from 73% to 88% for the 30% ecoregion representation target and from 73% to 98% for the 50% ecoregion representation target). 'Member state equity' generated the highest protection equality for member states' protected proportions but was the most expensive of the expansion scenarios. While the spatial distribution of additional PA across planning units differed for each scenario (Fig. II.3 and Fig. II.S6), there are some planning units where additional PA would be located for all three scenarios. Based on the SCP concept of irreplaceability, these are the sites of highest importance for achieving the respective ecoregion representation target (Watson et al. 2011). For both ecoregion representation targets, the model allocated most additional PAs for all three scenarios to semi-natural forests, followed by other semi- or natural ecosystems and arable land (Fig. II.4). A detailed analysis of the impacts the simulated network expansion could have on the forest and agricultural sector was out of the scope of this thesis. Section II contains the full research article published in the journal Conservation Biology.

5. Discussion of thesis' contributions to the research field and the debate on post-2020 European biodiversity protection

5.1 Novelty of the work presented in this thesis

The modeling framework and research presented in this thesis are supplements to previous studies for the evaluation of ecological representation within the EU's PA network. While most EU-level studies focus on selected species as biodiversity surrogates (Zisenis 2017), the framework developed here uses ecoregions and ecosystems as biodiversity surrogates. Comprehensive maps of terrestrial (Olson et al. 2001; Dinerstein et al. 2017b) and marine (Spalding et al. 2007) ecoregions exist. These datasets are not prone to the many difficulties associated with species distribution data based on inventories, such as incomplete spatial or temporal coverage (Soberón et al. 2007; Hortal et al. 2008) or coarse spatial resolution (Araújo 2004). While ecoregions were often used as biodiversity surrogates to evaluate ecological representation in global scale studies (Woodley et al. 2012; Tittensor et al. 2014; Watson et al. 2016; Gannon et al. 2019), only Beresford et al. (2016) conducted a gap analysis for ecoregions at the EU-level. However, the modeling framework in this study does not only present a gap analysis of the status quo of ecoregion protection, it also investigates how remaining gaps could be closed cost-efficiently. Additionally, it is the first study that incorporates habitat types or ecosystems as a secondary biodiversity surrogate refining the selection of additional conservation sites to increase overall biodiversity representation further.

A second novelty of the work presented in this thesis is the proactive evaluation of potential higher ecoregion representation targets. Ecologists have long argued for global protection targets that would go beyond Aichi Target 11's 17% benchmark (Watson & Venter 2017; Baillie & Zhang 2018; Ellis 2019). The zero draft of the CBD's post-2020 biodiversity strategy contains a 30% coverage target for the global PA extent (Working group on the post-2020 global biodiversity framework 2020).Furthermore, the European Parliament is calling for 30% PA coverage until 2030 and potentially raising this target globally to 50% in 2050 (European Parliament 2020). Even though signatory parties explicitly call for scenarios and models on a range of spatial scales to inform the development of post-2020 targets and strategies (Conference of the parties to the CBD 2018), no study has so far assessed higher conservation targets for the European Union. The research presented in the second study of this cumulative thesis closes this research gap by evaluating the network towards the goal of protecting 30% of each European ecoregion. With the evaluation against the second, much higher 50% ecoregion representation target, the thesis expands the gap analysis conducted by Dinerstein et al. (2017a). The study conducted for this thesis does not only report the status-quo but also offers simulated cost-efficient network expansion scenarios for the European Union.

5.2 Limitations

The research conducted for this thesis was subject to several limitations. Data quality and resolution affected the modeling framework design. The European Red List of habitat types used in the first study was only available at 10 km resolution. Therefore, the spatial overlay of habtitat type distribution with PAs that were available on a much finer resolution is subject to uncertainty, even though an approach to estimate protected and unprotected habitat areas was presented. For the second study, the 100 m resolution CORINE land cover dataset offered a much finer spatial resolution but was thematically restricted to only 18 semi- or natural ecosystem classes. Furthermore, not all datasets that could have substantially improved the network evaluation and expansion simulation were available at the EU level. While the member states' Article 17 reporting dataset contains spatially explicit information on the current conservation status of Annex I habitat types, it was too fragmentary for the 2007-2010 reporting period to be included to refine the modeling framework (European Environment Agency 2015). Similarly, management and restoration costs were not available on the EU-wide level and are difficult to estimate (Kotiaho & Moilanen 2015). Instead, observed agricultural land prizes on NUTS-3 regional level from the years 2007 and 2008 reported in a previous study (Jantke et al. 2016) served as proxies for opportunity costs in the first research article. For the second study, these were replaced by an average of more up to date land rent data, covering the period 2009-2015 (Farm Accountancy Data Network 2018), which were however only available on the coarser NUTS-2 regional level. In both studies, the allocation of additional PA remained on these relatively coarse spatial scales. If EU member states planned to implement the recommended additional PA described in the manuscripts, additional conservation planning exercises would be necessary to determine the most effective location of these PAs on the local scale.

5.3 Remarks on conservation targets

The aim of this thesis was not to re-calculate or justify existing conservation targets but to show how such targets could be systematically implemented in the EU's PA network. Nevertheless, the adequate amount of protection necessary to stop biodiversity loss is still unknown (Svancara et al. 2005; Laitila & Moilanen 2012). There is no scientific evidence proving that setting aside 30% or 50% of the EU's land area would be sufficient to achieve favorable conservation status for all species and habitats found within its borders. Research on PA effectiveness suggests this might depend on local implementation (McNeely 1994), enforcement (Hilborn et al. 2006; Nolte 2016) and management practices (Ostermann 1998; Kati et al. 2015). These factors are in turn often dependent on the availability of funding to either pay for reinforcement of legal measures (Leverington et al. 2010) or to offer adequate incentives for land users to stick to environment-friendly land uses voluntarily (Boxall et al. 2017; Schuster et al. 2018). On the other hand, Natura 2000 legislation does not prohibit land use practices as long as they ensure a favorable conservation status of European species and habitats. Many of the European semi-natural habitat types are the result of human land use and therefore need continued extensive management to persist into the future (Halada et al. 2011). Ambitious conservation targets, if implemented adequately, would lead to a large-scale reduction of environmental pressures stemming from high-intensity land uses, which would certainly improve the situation of European biodiversity. As the network expansion towards such higher conservation targets simulated in this thesis allocated the majority of the additional conservation area to forests, a co-benefit could be an increase in carbon stocks. Such a climate change mitigation potential was for example demonstrated for Mediterranean forest types located within PAs (Lecina-Diaz et al. 2019). In the long term, it might be necessary to transform the entire land use sector, adopting sustainable and biodiversity-friendly land use practices not only within PA but also across the whole EU territory to achieve the goal of ensuring persistence of European biodiversity into the future (Muller et al. 2017; Kok et al. 2018; Ellis 2019). Many species that can also exist close to human activities, such as insects, would benefit from organic farming practices (Hole et al. 2005; Habel et al. 2019). Switching from conventional to integrated farming practices might already restore taxon richness while still providing comparable yields (Katayama et al. 2019).

5.4 Implications of the thesis' findings

The expansion of the EU's PA network towards more ambitious ecoregion coverage targets would require the inclusion of intensively used forests and arable land areas for some ecoregions. Protection regimes often restrict land management intensity, leading to local yield losses (Henle et al. 2008). Land users and owners fear the economic consequences an ambitious PA expansion might pose on them (Koemle et al. 2019). For ambitious PA expansion plans, such as the proposed Half-Earth vision, the summed land management restrictions on additionally required PA could cause a substantial decrease or shift in the production of agricultural commodities (Mehrabi et al. 2018). In our globalized world, the EU land use sector is linked to the rest of the world through international trade's demand and supply chains. Implementing conservation measures in one part of the world has often triggered unintended negative impacts on biodiversity in other parts of the world, referred to as leakage effect (Kuik 2014; Latawiec et al. 2015). To assess the overall socioeconomic and environmental impacts of national land use policy options, it is mandatory to consider these teleconnections (Bruckner et al. 2015). To sustain current European consumption levels, indirect land grabbing is already a problem today with the EU being the world's largest net importer of agricultural products, especially of soybeans from South America (Tscharntke et al. 2012). An expansion of the reserve network could further escalate this issue. A previous study modeling the impacts of increasing the PA network extent by 26% in the European Union did find that the loss of agricultural yields within PAs could be only partly compensated for within the EU by higher management intensities outside PAs. The results showed particularly that production of agricultural goods was shifted from Europe to other parts of the world where land would on average be less productive, leading e.g. to a decrease in tropical forest area (Lotze-Campen et al. 2018). From the global perspective, the potential for further increases in yields through management intensification is rather limited in the industrialized agricultural systems that are prevalent in Europe (Zabel et al. 2019). Avoiding negative biodiversity leakage effects in other parts of the world was only feasible in scenarios including a decrease in European consumption, especially in the consumption of animal products (Poux & Aubert 2018; Rega et al. 2019). Therefore, the next research question following from this thesis's findings would be what impacts the proposed PA network expansion within the EU would have on the EU's domestic and the global land use sector. In the past, biodiversity has often only been weakly implemented in integrated assessment models (Hill et al. 2016). Yet it is possible to couple spatial prioritization models to land use sector models (Lagabrielle et al. 2010).

5.5 Overall summary and conclusion

The framework presented in this thesis is the first that evaluates and improves the representation of non-species biodiversity surrogates for the EU's full PA extent. It uses recently developed representation metrics for the gap analysis and provides a cost-efficient simulation of network expansion founded on the best available EU-level proxy data for forgone opportunity cost. It is also the first study that incorporates habitat types or ecosystems as a secondary biodiversity surrogate refining the selection of additional conservation sites to increase overall biodiversity representation further.

The thesis' findings offer valuable information for the EU's post-2020 biodiversity strategy debate. They point out remaining gaps towards the representation of ecoregions in the Natura 2000 network as defined by the current Aichi Target 11 that the EU as a signatory party of the CBD was obliged to fulfill until 2020. Additionally, the thesis proactively explored gaps towards potential higher ecoregion coverage targets. It identified member states that would need to expand their national PA networks and land cover types most targeted if the network was expanded systematically and cost-efficiently. These findings offer insights for further discussions on the future of biodiversity conservation in the European Union.

6. References

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I

Is large good enough? Evaluating and improving representation of ecoregions and habitat types in the European Union's protected area network Natura 2000

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Abstract. Natura 2000, the largest protected area network worldwide, covers 18.2% of the European Union's terrestrial area. Thereby, the network surpasses the goal of the Convention on Biological Diversity's Aichi Target 11 to protect 17% of the land area by 2020. However, Aichi Target 11 also calls for protected area networks to be ecologically representative. Here, we analyzed the coverage of 43 ecoregions in the terrestrial Natura 2000 estate. To simulate cost-efficient closing of gaps in the current system, we applied a linear programming model that solves the minimum set conservation problem of expanding the Natura 2000 network to achieve 10% ecoregion representation. As Natura 2000 sites are designated for habitat types and species listed on the annexes of the Habitats and Birds Directives, we included 226 habitat types as a further biodiversity surrogate in the optimization. We found six ecoregions that currently do not meet the 10% representation target. To close these gaps, an additional 15 187 km² (0.35% of the European Union's land territory) would be required. Simultaneously, representation of 21 habitat types could be increased. The United Kingdom would have to contribute more than half of the additional area, followed by Estonia, Latvia, France, and Italy. To protect biodiversity effectively and to comply with international conservation targets such as Aichi Target 11, we recommend continuous evaluation and improvement also of already well-established protected area networks.

Keywords: Natura 2000, Linear Programming Model, Systematic Conservation Planning, Ecological Representation, Protected Area Network, Aichi Target 11

1. Introduction

To stop biodiversity loss, nations adopted the Convention on Biological Diversity (CBD) more than 25 years ago, and 196 parties signed it to date. The current Strategic Plan for Biodiversity 2011-2020 contains 20 so-called Aichi targets that each signatory party should achieve until 2020 (Conference of the parties to the CBD 2010). As signatory parties only reluctantly implement the CBD (Ulloa et al. 2018), global biodiversity loss will likely continue beyond 2020 (Tittensor et al. 2014). Evaluations of achievements towards the Aichi targets can help to inform policymakers where to concentrate future conservation efforts.

The European Union (EU) adopted the Birds and the Habitats directives to fulfill its obligations under the CBD. These directives demand the creation of an EU-wide network of protected areas (PAs). Today, Natura 2000 is one of the world's largest conservation networks currently covering more than 18% of the EU's terrestrial territory (European Commission 2018). With this, the terrestrial Natura 2000 estate formally surpasses the areal component of Aichi Target 11, which calls for at least 17% of terrestrial areas to be conserved. The network is considered nearly complete (Evans 2012) and a substantial further expansion seems unlikely (Orlikowska et al. 2016). Nevertheless, it remains unclear if the current network extent ensures effective protection of European biodiversity.

Measures of progress towards effective conservation have focused on simplistic areal assessments, such as total area protected (Tittensor et al. 2014; UNEP-WCMC & IUCN 2016; Watson et al. 2016; Barnes et al. 2018). Principles of systematic conservation planning, however, also require adequate representation of biodiversity features in reserve systems (Margules & Pressey 2000; Moilanen et al. 2009). Aichi Target 11 explicitly considers this aspect and calls for PA networks to be "ecologically representative" (Conference of the parties to the CBD 2010). While the lack of indicators has hampered the measurement of representation (Di Marco et al. 2016; Watson et al. 2016), newly developed metrics such as 'protection equality' (Chauvenet et al. 2017) and 'mean target achievement' (Jantke et al. 2019) provide a timely opportunity to address this task.

Previous assessments of the entire EU or European continent often used species as biodiversity surrogates, e.g. evaluating representation of species listed on Annex II of the Habitats directive (Gruber et al. 2012), terrestrial vertebrates (Maiorano et al. 2015; Kukkala et al. 2016a), birds (Kukkala et al. 2016b), amphibians and reptiles (Sánchez-Fernández & Abellán 2015), wetland vertebrates (Jantke et al. 2011), or threatened species (Trochet & Schmeller 2013) – for a detailed summary of the results of these studies, please see Zisenis (2017) as well as Orlikowska et al. (2016), who provide comprehensive reviews of ecological research conducted for the Natura 2000 network. While these studies offer valuable insights into the coverage of the respective species groups, they neglect further important components of biodiversity, e.g., invertebrate or microscopic organisms, for which distribution data is not yet available (Hill et al. 2016). To capture biodiversity in general, conservation plans could, therefore, focus on broader surrogates such as ecosystems (Franklin 1993), species and ecosystems simultaneously (Polak et al. 2015), or ecoregions (Dinerstein et al. 2017a).

Few studies assessed ecological representation in the entire Natura 2000 network based on non-species surrogates, such as biogeographical regions (European Environment Agency 2012) and ecoregions (Beresford et al. 2016). While previous studies focused on evaluations of the current network, specific recommendations for effective expansion are scarce (Kukkala et al. 2016a; Kukkala et al. 2016b; Diserens et al. 2017) and even fewer studies provide assessments that explore cost-efficient enlargement of the Natura 2000 network (Jantke et al. 2011; Petersen et al. 2016).

The primary goal of our study is to evaluate to what degree the Natura 2000 network already fulfills the representation element of Aichi Target 11. The technical rationale to Aichi Target 11 gives further detail on ecological representation and states that "protected area systems should contain adequate samples of the full range of existing ecosystems and ecological processes, including at least 10% of each ecoregion within the country" (Convention on Biological Diversity 2013). Consequently, the Natura 2000 network should at least cover 10% of each European ecoregion to fully comply with the representation element of Aichi Target 11. Nevertheless, ecoregions are broadly defined biodiversity surrogates, while Natura 2000 sites designation specifically targets species and habitat types listed in the annexes of the Habitats and Birds Directives. While simply protecting any natural area within an ecoregion might be sufficient to meet the ecoregion's representation target, such areas are not necessarily priority areas for conservation. Therefore, we include habitat types as a second biodiversity surrogate in our analysis.

We evaluate the status of the Natura 2000 network and identify future action needed to comply with CBD's Aichi Target 11 by (1) assessing the representation of ecoregions and habitat types in Natura 2000 and (2) simulating cost-efficient expansion of the network to achieve 10% ecoregion representation while improving habitat type representation as well. We provide specific information on strategic conservation planning relevant to the development of post-2020 targets for the EU's nature conservation policies.

2. Methods

2.1 Study area

The EU has 28 member states and a total human population of c. 500 million people (about 7% of the world's population). In 2016, the EU accounted with 21.7% for the second-largest share of global GDP exceeded only by the United States with 24.5%

(The World Bank 2016). With a terrestrial area of c. 4.2 million km², the EU covers the major part of the European continent. We exclude all member states' territories that do not belong to the Palearctic realm from our analysis. We also exclude the Azores due to data deficiencies.

PAs under the Natura 2000 scheme are established for characteristic and threatened species and habitats. Natura 2000 sites protect 231 habitat types listed in Annex I and about 900 species listed in Annex II of the Habitats directive as well as about 194 bird species listed in Annex I of the Birds directive. By the end of 2017, the terrestrial network covered 789 868 km² (18.2% of the EU's terrestrial territory). PA coverage differs between member states, ranging from 8.3% in Denmark to 37.9% in Slovenia (European Commission 2018). The size of Natura 2000 sites ranges considerably from 1 m² ("Bradlo" in Slovakia) to 320 km² ("Tornionjoen-Muonionjoen vesistöalue" in Finland). The rigor of protection of Natura 2000 sites depends on national legislation and therefore differs within and between member states.

2.2 Data

2.2.1 Protected areas, ecoregions and habitat types

We used the most recent data (end of 2017) on the extent of the Natura 2000 estate (Directorate-General for Environment 2017) for all calculations of protected areas. We obtained spatial data on the distribution of ecoregions from the Ecoregions 2017 © Resolve map (Dinerstein et al. 2017b). The study region captures 43 ecoregions. We calculated the total area of each ecoregion in the EU (a_e) as well as the area of each ecoregion protected by the Natura 2000 network (p_e). We obtained data on the distribution of habitat types in 10 km resolution from the European Red List of habitats (European Commission 2016). Our study region captures 226 of the 233 habitat types, listed according to EUNIS habitat classification level 3. This dataset contains the best available information on habitat type distribution in Europe to date, and while it differs to some extent from the classification used in Annex I of the Habitats directive, the classification detail is similar.

The European Red List of habitats provides only presence-absence data on habitat types. To estimate the area of each habitat type within each 10 km grid cell, we used data on the spatial distribution of ecosystems classified according to EUNIS habitat classification level 1 in 100 m resolution from The Ecosystems of Europe (European Environment Agency 2015) dataset. We linked habitat type and ecosystem data based on the EUNIS classification level 1. Particularly, we assumed that if a habitat type was present in a grid cell, its spatial distribution would be confined to the extent of the matching ecosystem's spatial distribution in this cell. We calculated protected and unprotected ecosystem area per grid cell. From this, we estimated the protected (p_h) and total area (a_h) of each habitat type within each 10 km grid cell. For a detailed description of the approach, see Appendix I.

2.2.2 Land cost and planning units

We used observed agricultural land prices at NUTS-3 (Nomenclature des unités territoriales statistiques - Classification of Territorial Units for Statistics) region level from Jantke et al. (2016) as proxies for conservation cost. Our model is based on 1956 planning units, obtained by intersecting the NUTS-3 regions (EuroGeographics 2013) and ecoregions. The optimization model does not select entire planning units as additional priority areas for conservation, but only the fractions that are needed to fulfill representation targets.

2.3 Metrics and model

2.3.1 Representation metrics

We applied the mean target achievement (MTA) metric (Jantke et al. 2019) with the R package ConsTarget (Jantke et al. 2018a) to evaluate if all ecoregions achieve 10% representation in the Natura 2000 network. The metric calculates the degree of conservation target achievement for all ecoregions. It outputs a value between 0 and 1, with 0 indicating that no ecoregion receives any protection and 1 indicating that each ecoregion fulfills the 10% representation target.

The technical rationale to Aichi Target 11 only provides representation targets for ecoregions. Thus, we evaluated representation of habitat types with the proportional protection equality (PE) metric (Chauvenet et al. 2017) using the R package ProtectEqual (Chauvenet et al. 2015). The PE metric measures how homogeneously a PA network protects biodiversity features, such as species, habitat types, or biomes. It outputs a value between 0 and 1, with 0 indicating a heterogeneous and 1 indicating a perfectly homogenous habitat type representation in the Natura 2000 network.

We used ArcMap 10.3.1 (ESRI (n.d.)) for GIS analyses and R version 3.3.3 (R Core Team 2017) to calculate the metrics.

2.3.2 Optimization model

Designing a cost-effective network expansion to fulfill a given conservation target is a classical minimum set conservation planning problem (Margules & Sarkar 2007). We used a conservation target of 10% representation for each European ecoregion in the Natura 2000 network. In addition, we aligned the representation of habitat types occurring in the gap ecoregions as much as possible. Thus, we have three objectives in a strict lexicographic order. The first objective specifies the representation target for all ecoregions. The second objective tries to protect all habitat types as homogenously as possible. The third objective seeks to achieve both previous objectives at minimal cost. We developed a linear programming-based modeling system consisting of two individual optimization models to solve the overall allocation problem (Figure I.5)

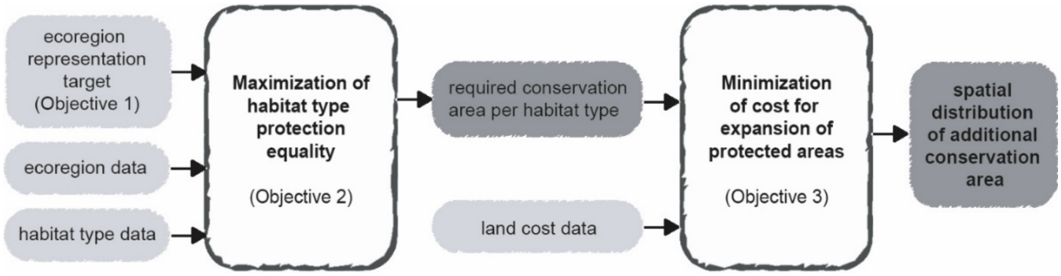

Figure I.1 *Overview of modeling approach. Light grey boxes depict input data, dark grey boxes output data and white boxes with dark fringes show analysis tools.*

We used the following notation: $p = \{p_1,\ldots,p_{1956}\}$ is the set of planning units, $e = \{e_1,\ldots,e_{43}\}$ is the set of gap ecoregions, and $h = \{h_1,\ldots,h_{226}\}$ is the set of all habitat types occurring in at least one gap ecoregion. The index $I = \{i_1,\ldots,i_k\}$ contains as many elements as necessary to achieve objective 2. The variable L is an auxiliary objective variable and represents the lowest representation in Natura 2000 among selected habitat types *h* occurring in ecoregion *e*. The non-negative variable array R depicts the representation of habitat type *h* in Natura 2000, and the non-negative variable array A represents the additional conservation area (in ha) each habitat type *h* requires in each ecoregion *e*. The variable O represents total land cost (in billion €). The non-negative variable array Y depicts the additional required conservation area (in 1000 ha) per planning unit *p*, ecoregion *e*, and habitat type *h*. We used several exogenous datasets. The parameter c depicts the agricultural land costs (in €/ha) per planning unit *p*. u depicts the unprotected and p the protected area (in ha) of ecoregion *e* in the entire EU. q depicts the unprotected and r the protected area (in ha) in planning unit *p*, ecoregion *e*, and habitat type *h*. Finally, t represents the representation target per ecoregion *e* as a value from 0 to 1 (set to 0.1 for each ecoregion *e* to fulfill the 10% representation target).

The first model (equations [1]-[6]) operates at a coarser scale and addresses only the allocation of habitats within ecoregions. The model determines for a given ecoregion target (objective 1) the most homogenous representation of all habitat types (objective 2) by expanding their protected area in gap ecoregions. The technical realization of this optimization process involves a sequence of model solutions depicted by the index i. The objective cannot be higher than the lowest representation of all included habitat types (Equation [2]). In all repetitions, we enforce the achievement of objective 1, i.e. the expansion of protected areas in all gap ecoregions such that the representation target of 10% is exactly fulfilled (equation [3]). The first model execution ($i = i_1$) includes all habitats in the optimization process. Hence, all habitat types can expand their protected area to achieve the conservation target. In this initial optimization, the set of previously optimized habitat types (h^*) is empty. While equations [2], [4], and [5] apply to all habitats, equation [6] is not used in the initial model execution. Equation [4] limits the expansion of protected areas to not exceed the remaining unprotected area for each habitat type. Equation [5] calculates the new representation level for all expanded habitat types. Note that representation of habitat types is computed as share of protected habitat area relative to total habitat area across all ecoregions specifically including ecoregions without gap. The initial optimization identifies the highest general representation level that all individual habitat types can achieve. From this solution, we add the habitat with the lowest representation, i.e. the habitat type for which $P_h^* = L^*$, to the set h^*. The next model execution ($i = i_2$) maximizes the lowest representation value for all remaining habitat types ($h \notin h^*$) but forces the protected area expansion of the habitat type included in h^* to remain at the previously found solution level (equation [6]). After the second solution has been found, the habitat with the lowest representation level is again added to the set h^*. This process continues until all habitat types are added to h^*. From each solution to the next, the optimal value of L increases.

Allocation model I: Homogenous alignment of protected habitats

$$Maximize\ \ L \qquad \forall i \qquad [1]$$

$$L \le R_h \qquad \forall h \notin h^* \qquad [2]$$

$$p_e + \sum_h A_{e,h} = \left(u_e + p_e\right) \cdot t_e \qquad \forall e \qquad [3]$$

$$A_{e,h} \le \sum_p q_{p,e,h} \qquad \forall e, h \notin h^* \qquad [4]$$

$$R_h = \frac{\sum_e \left(A_{e,h} + \sum_p r_{p,e,h} \right)}{\sum_{p,e} \left(q_{p,e,h} + r_{p,e,h} \right)} \qquad \forall h \notin h^* \qquad [5]$$

$$A_{e,h} = A_{e,h}^* \qquad \forall e, h \in h^* \qquad [6]$$

Allocation model II: Cost-effective expansion of protected areas

$$Minimize\ \ O \qquad [7]$$

$$O = \sum_{p,e,h} \left(c_p \cdot Y_{p,e,h} / 10^6 \right) \qquad \forall p \qquad [8]$$

$$Y_{p,e,h} \le q_{p,e,h} \qquad \forall p, e, h \qquad [9]$$

$$\sum_p Y_{p,e,h} = A_{e,h}^* \qquad \forall e, h \qquad [10]$$

The second model (equations [7] to [10]) uses a higher spatial resolution and determines the cost-minimizing expansion of protected habitat areas within the 1956 planning units (objective 3). This linear minimization model is subject to three constraints. Equation [8] computes the total opportunity cost as the product of additional selected area per planning unit times land cost summed over all planning units. Constraint [9] limits selectable habitat type area in each planning unit to available unprotected habitat type area. Constraint [10] enforces consistency between the solution of the second model and the solution of the first model. The two models were implemented in GAMS version 24.8.3 and solved using the CPLEX algorithm. At the end of the two-stage optimization process, we recalculated the MTA and PE metrics with the simulated PA coverage data for ecoregions and habitats (p_e and p_h).

3. Results

3.1 Representation of ecoregions and habitat types in the Natura 2000 network

The Natura 2000 network covers 18.2% of the terrestrial EU, fulfilling the areal component of Aichi Target 11. We found 96% mean target achievement across 43 ecoregions in the Natura 2000 network. 37 ecoregions surpass the 10% representation level, 31 ecoregions surpass 20% and four ecoregions even 50% PA coverage (Fig. I.2). Small ecoregions often achieve high representation. Because smaller ecoregions are mainly located in the Southern part of Europe, most ecoregions with representation levels above 25% can be found there (Fig. I.3).

Table I.1 *Gap ecoregions. Ecoregions that do not meet the 10% representation target in Natura 2000 and conservation area that would need to be added to Natura 2000 to reach 10% representation.*

ecoregion	representation in the current Natura 2000 network [%]	additional conservation area [km²]
English Lowlands beech forests	3.2	3059
Celtic broadleaf forests	7.3	5613
Po basin mixed forests	7.4	1073
East European forest steppe	7.6	488
Sarmatic mixed forests	8.9	2839
European Atlantic mixed forests	9.4	2114
Total	-	**15 187**

Figure I.2 *Representation of European ecoregions in the Natura 2000 network.*

Despite a high degree of mean target achievement across the Natura 2000 network, six ecoregions fail to meet the 10% representation target (Table I.1, Fig. I.2). While the PA coverage of the two regions Sarmatic mixed forests and European Atlantic mixed forests is just below the target level, only 3% of the English Lowlands beech forests are protected by Natura 2000 sites. If the current network extent is to be maintained, another 15,187 km² (0.35% of the terrestrial EU area) is required to achieve 10% representation of all European ecoregions (Table I.1). Protection equality across 226 habitat types in Natura 2000 is currently 72% with representation levels ranging from 7.5% for *Arable land with unmixed crops grown by low-intensity agricultural methods (I1.3)* to 96.2% for *Eastern Mediterranean base-rich scree (H2.6c)*. While habitat type I1.3, which is threatened by both agricultural intensification and abandonment of agriculture, does not have an equivalent Habitats Directive Annex I habitat, H2.6c relates to two Annex I habitat types. The scree's range is naturally restricted because its establishment requires very specific environmental conditions. Additionally, screes are not fit for most other land uses. As protected area designation is often biased towards higher elevations and land with low agricultural potential (Gaston et al. 2008), it is not surprising that member states already designated large parts of this habitat type as Natura 2000 sites. Over all, representation levels of 197 habitat types were higher than 20%, while only 29 out of 226 habitat types are covered at levels below 20%. For a table containing the representation levels of all 226 habitat types see the supplementary material (Supplementary, Table I.S1).

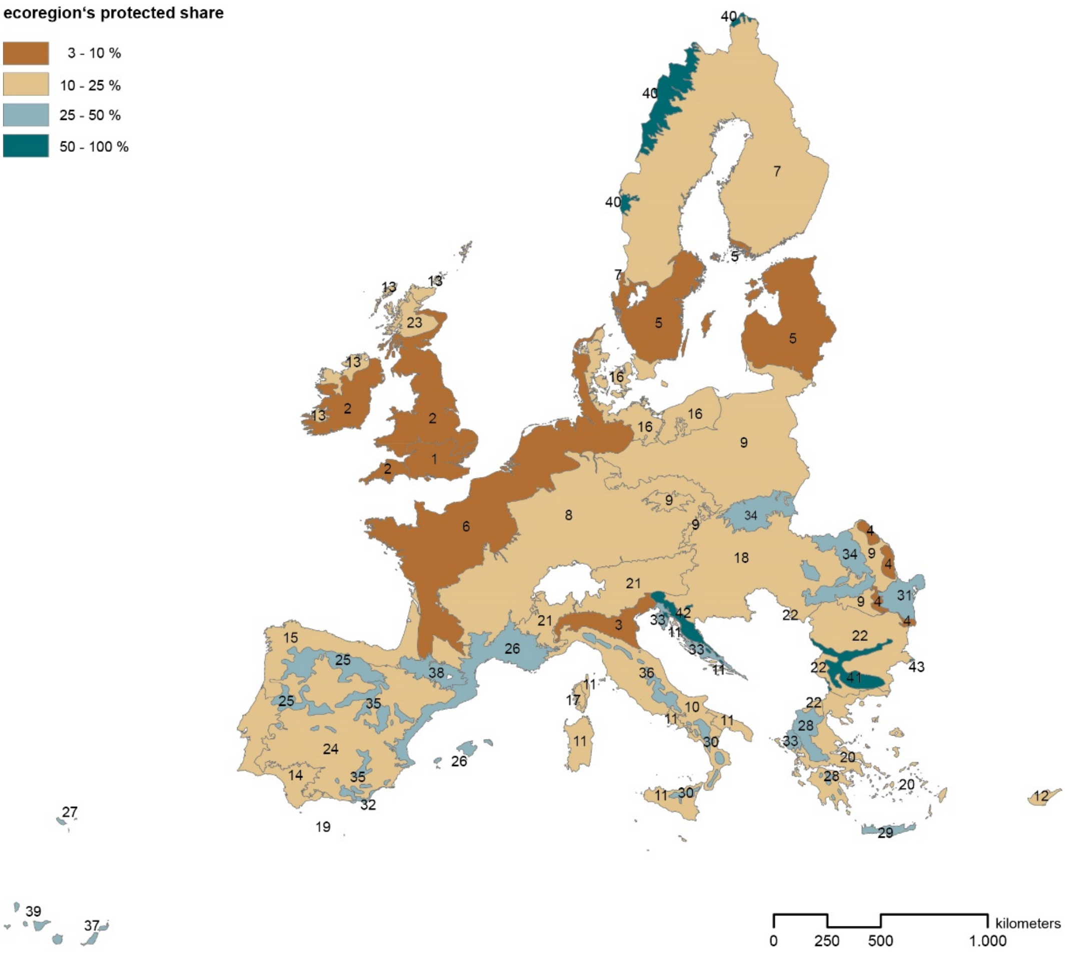

Figure I.3 *Protected share of each of the 43 European ecoregions. Label numbers correspond to ecoregions in Figure I.2.*

3.2 Cost-efficient expansion of the Natura 2000 network

Although the current Natura 2000 estate fulfills the areal component of Aichi Target 11, which is 17% of the terrestrial area under protection, it fails to protect six ecoregions adequately. To meet the 10% representation targets for the gap ecoregions cost-effectively, 11 EU member states should expand their PA network by a total of 15,187 km² (Fig. I.4).

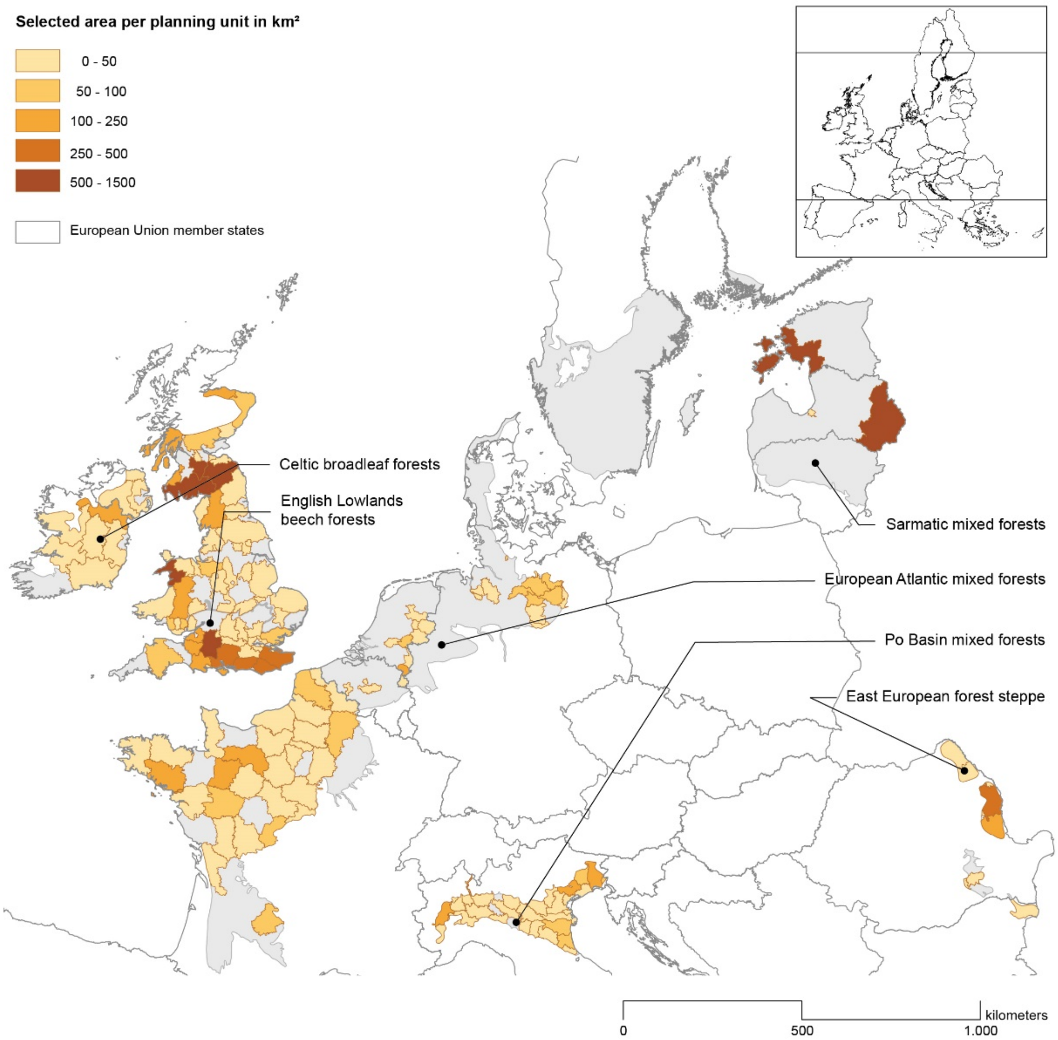

Figure I.4 *Spatial distribution of additional conservation area across six gap ecoregions.*

55% of the additional conservation area should be allocated in the United Kingdom, followed by Estonia (10%), Latvia (9%), France (8%), and Italy (7%). Further network expansion would occur in Germany, Romania, The Netherlands, Ireland, Belgium, and Bulgaria (Fig. I.5A). Most gap ecoregions cover areas of only one or two member states, leaving limited scope for the allocation of the necessary additional protected areas. Only Sarmatic mixed forests and European Atlantic mixed forests have a wider distribution. They also occur in Scandinavian member states, which are not part of our model's outcome due to high land costs in these countries. A cost-effective expansion could benefit 21 out of 226 habitat types; about half of the area is allocated to four grassland habitat types and nearly 20% to two taiga woodland habitat types (Fig. I.5B). At the same time, protection equality across all 226 habitat types would increase from 72% to 73%.

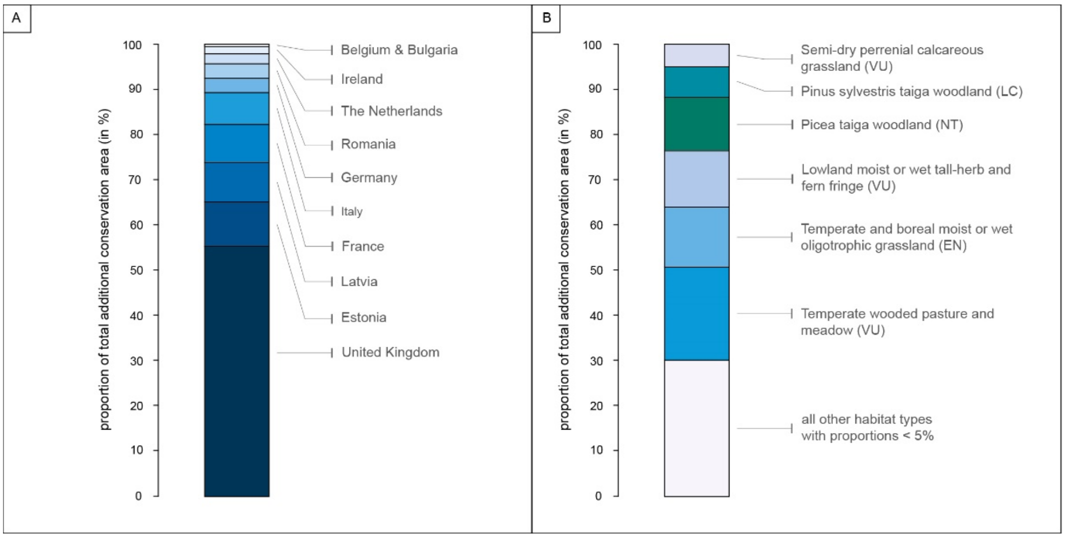

Figure I.5 *Member states' shares (A) and habitat types' shares (B) of additional conservation area. European Red List categories: least concern (LC), near threatened (NT), vulnerable (VU), endangered (EN).*

4. Discussion

European biodiversity continues to decline (IPBES 2018). Protected area estates that could help reverse this trend have grown considerably during the last decades. However, our results show that the terrestrial Natura 2000 network, despite being large, is not fully representative of European ecoregions. Because six ecoregions do not meet the 10% representation target of Aichi Target 11's guidelines, we suggest expanding the current Natura 2000 network by another 15,187 km². Habitat type representation in the current PA estate as measured by protection equality could increase marginally (by 1%) if the Natura 2000 network was expanded strategically. Our analyses, however, reveal that current representation of habitat types in the Natura 2000 system is already high relative to PE levels found for terrestrial ecoregions (median PE across terrestrial ecoregions for 83 countries = 0.42 [Barr et al. 2011]), marine ecoregions (PE across 258 marine ecoregions = 0.31 [Jantke et al. 2018b]), marine bioregions around Australia (PE across 85 marine bioregions = 0.19-0.24 [Barr & Possingham 2013]) or specific marine sites such as the Coral Triangle region (PE = 0.38-0.44 [Chauvenet et al. 2017]).

Our findings match well with the Natura 2000 barometer's national Natura 2000 network evaluation conducted for each member state (European Commission 2017). Notable differences were only found for Ireland. While Ireland's network should be complete according to the Natura 2000 barometer, our findings suggest that a small amount of additional PA's should still be designated in order to close the representation gap of the ecoregion Celtic broadleaf forests. Kukkala et al. (2016b) identified priority areas for a Natura 2000 expansion to cover 17% of the EU terrestrial and inland water areas while simultaneously maximizing vertebrate species representation in the network and suggest expansions in all member states except

Luxembourg, with proposed PAs mainly distributed across Spain, Finland, Greece and the United Kingdom. Among these countries, we only identified the United Kingdom as a possible contributor to network expansion. An evaluation of the Natura 2000 network for 70 vertebrate wetland species suggests that in order to cover at least one viable population of each species, the network could be expanded cost-efficiently in Latvia, Finland, Estonia and Romania (Jantke et al. 2011). Except for Finland, our findings suggest expansion in the same countries. As size and spatial distribution of priority areas for conservation strongly depend on biodiversity surrogates (Polak et al. 2015) and conservation targets (Vimal et al. 2011), it is not surprising that previous assessments produced different recommendations on where and how much to expand the Natura 2000 network. However, the bottom line of all studies, regardless of biodiversity surrogates and targets, is that the current Natura 2000 network should be expanded in order to fully represent and effectively protect European biodiversity.

While we simulate optimal expansion for a 10% ecoregion coverage, we acknowledge that 10% of each region under protection does not guarantee effective conservation of Europe's biodiversity. Conservation targets have repeatedly been criticized for being set arbitrarily and too low, especially when the targets were negotiated in political arenas rather than based on scientific evidence (Soule & Sanjayan 1998; Svancara et al. 2005; Carwardine et al. 2009; Noss et al. 2012). While the discussion on adequate PA coverage levels is ongoing, our research identifies European ecoregions and habitats most in need of further protection.

We show that the Natura 2000 network is not fully ecologically representative, but our work is subject to inevitable limitations. First, a major challenge for this study was the availability and quality of habitat types distribution data. Despite suggestions to estimate spatial distributions of Natura 2000 habitat types using predictive models (Mücher et al. 2009) or predictive models and remote sensing (Álvarez-Martínez et al. 2018), so far no distribution maps for the 231 Annex I habitat types exist. Currently, the European Red List of habitat types (European Commission 2016) provides the best data on European habitat type distribution, even though it is based on various data sources of varying quality. We present an approach to estimate protected and unprotected habitat area based on the available datasets but would nevertheless like the reader to consider our habitat type representation levels with caution. We checked the estimated total habitat type areas against the current estimated total areas reported in the European Red List of habitat types and noted that our estimated habitat type areas overestimate some total habitat type areas reported there. To improve future analyses and provide better policy advice, we reiterate the urgent need to develop higher resolution data on habitat types in Europe. Second, we used land opportunity costs from acquiring land for conservation as proxies for conservation cost. We could not consider important additional costs, such as costs of reserve establishment and maintenance (Naidoo et al. 2006). Although there have been attempts to estimate for example management costs on national levels (Petersen et al. 2016), such data is not available for all European member states and the 226 habitat types we considered in our analysis. When implementing site selection algorithms based on cost data, the most cost-efficient solution is not necessarily also the ecologically most reasonable. In this study, we increase habitat type representation prior to the minimization of land costs. This ensures model solutions that are ecologically more meaningful than model solutions selecting additional conservation areas solely based on land cost data. A further improvement would be to also incorporate habitat quality in the model. Robust habitat quality data at the grid cell level is, however, currently not available.

Continuous evaluation and improvement of PA networks is one important strategy to progress towards effective biodiversity protection. Ensuring adequate ecological representation within a PA network is, however, only a prerequisite. Even the most representative PA network is pointless without effective enforcement and management of protected sites on the ground to achieve or maintain favorable conservation status of species and habitat types. Only then can PA estates such as the Natura 2000 network reach their full protection potential.

5. Conclusion

By adopting the Convention on Biological Diversity 25 years ago, nations pledged to stop biodiversity loss, but this goal is still not within reach. Our study demonstrates how the EU could comply with the representation requirement of Aichi Target 11 to protect 10% of each ecoregion by adding another 0.35% of the terrestrial EU territory to the current Natura 2000 estate. We show how network expansion can be designed strategically to increase coverage of habitat types that currently have the lowest representation levels. By taking into account conservation costs when selecting target regions for network expansion, we also show which member states should further expand their national Natura 2000 estates in order to achieve a cost-effective solution on the EU scale. Our research thereby offers valuable results that should inform the EU's discussion on post-2020 targets and plans for further improvement of its unique nature protection network.

6. References

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Appendix I

We calculated protected and unprotected area of the eight EUNIS level 1 ecosystems per 10 km cell from the areas reported in the Ecosystem of Europe dataset on 100 m resolution. We then estimated the protected and unprotected area of each European Red List habitat type (classified according to EUNIS level 3) per 10 km cell based on the protected and unprotected EUNIS level 1 ecosystem area in this cell. We use the following notation: $c = \{c_1,\ldots,c_{47270}\}$ is the set of 10 km cells, $e = \{e_1,\ldots,e_{43}\}$ is the set of ecoregions, $l = \{l_1,\ldots,l_8\}$ is the set of EUNIS level 1 ecosystems and $h = \{h_1,\ldots,h_{226}\}$ is the set of EUNIS level 3 habitat types. $s = \{s_0,s_1\}$ is the set of protection states with s_0 = unprotected and s_1 = protected. The set mapping m (l, h) links EUNIS level 1 ecosystems to EUNIS level 3 habitat types. The parameter a denotes the area of a EUNIS level 3 habitat type h in grid cell c and ecoregion e with protection state s (in ha). b is the area of a EUNIS level 1 ecosystem l in grid cell c and ecoregion e with protection state s (in ha). Finally, d is the number of EUNIS level 3 habitat types h matching a EUNIS level 1 ecosystem l in a cell c. We use the following equation:

$$a_{c,e,h,s} = \sum_{l \in m(l,h)} \left(\frac{b_{c,e,l,s}}{d_{c,l}} \right) \qquad \forall c,e,h,s \qquad \text{[A.1]}$$

Equation [1] calculates the (un)protected area of a EUNIS level 3 habitat type in cell c and ecoregion e as the (un)protected area of the associated EUNIS level 1 ecosystem l in the same ecoregion e and cell c divided by the number of EUNIS level 3 habitat types h matching this EUNIS level 1 ecosystem l in this cell c. We aggregate the resulting protected and unprotected habitat type areas from each cell c to calculate protected and unprotected habitat type area per planning unit p.

Supplementary

Table I.S1 *Evaluation of European Red List of habitat types' representation in the current Natura 2000 network. Threat categories are taken from European Red List of habitat types: critically endangered (CR), endangered (EN), vulnerable (VU), near threatened (NT), least concern (LC), data deficient (DD).*

Habitat type	Type code	Threat category	Estimated protected area [ha]*	Estimated total area [ha]*	Protected proportion [%]
Arable land with unmixed crops grown by low-intensity agricultural methods	I1.3	EN	51247.0	682999.0	7.5
Pinus sylvestris taiga woodland	G3.B	LC	500927.9	6054624.1	8.3
Picea taiga woodland	G3.A	NT	1225928.2	14192862	8.6
Hemiboreal and boreal wooded pasture and meadow	E7.2	CR	28417.3	313262.1	9.1
Heavy-metal grassland in Western and Central Europe	E1.B	EN	19714.7	196620.8	10
Temperate wooded pasture and meadow	E7.1	VU	654723.4	6112644.3	10.7
Mainland laurophyllous woodland	G2.2	LC	67119.9	618543.5	10.9
Moist or wet mesotrophic to eutrophic pasture	E3.4b	EN	25567.1	229473.7	11.1
Thermophile woodland fringe of acidic soils	E5.2b	LC	164539.5	1419984.3	11.6
Temperate and boreal moist or wet oligotrophic grassland	E3.5	EN	584121.3	4966659.7	11.8
Mesic permanent pasture of lowlands and mountains	E2.1a	VU	139244.3	1166782.6	11.9
Lowland to submontane, dry to mesic Nardus grassland	E1.7	VU	198793.5	1660983.2	12
Atlantic and Baltic rocky sea cliff and shore	B3.1a	LC	934.9	7754.3	12.1

Temperate temporary running watercourse	C2.5a	DD	56.7	466.5	12.2
Lowland moist or wet tall-herb and fern fringe	E5.4	VU	713369.1	5697382.8	12.5
Semi-dry perennial calcareous grassland	E1.2a	VU	403786.9	3074342.5	13.1
South-Aegean Phoenix grove	G2.5a	LC	1671.4	11047.8	15.1
Pinus mire woodland	G3.Da	VU	1658987.4	10901142.5	15.2
Picea mire woodland	G3.Db	EN	1662229.2	10898665.7	15.3
Broadleaved bog woodland on acid peat	G1.5	VU	1704305.9	11086147.7	15.4
Low steppic scrub	F3.1f	LC	16532.8	103989.4	15.9
Low and medium altitude hay meadow	E2.2	VU	714112.3	4371065.8	16.3
Atlantic, Baltic and Arctic coastal shingle beach	B2.1a	LC	1240.7	7206.6	17.2
Perennial rocky grassland of the Italian Peninsula	E1.1e	VU	47235.4	269287	17.5
Moist or wet mesotrophic to eutrophic hay meadow	E3.4a	EN	841682.8	4789854.3	17.6
Permanent non-tidal, fast, turbulent watercourse of plains and montane regions with Ranunculus spp.	C2.2b	VU	203274.9	1107990.8	18.3
Atlantic coastal salt marsh	A2.5c	VU	4389.1	23542.5	18.6
Perennial rocky calcareous grassland of subatlantic-submediterranean Europe	E1.1i	VU	23651.2	124310.1	19
Acidophilous Quercus woodland	G1.8	VU	1135693.3	5763100.9	19.7
Eastern Mediterranean spiny heath (phrygana)	F7.3	LC	116307.1	554428.5	21.0
Atlantic and Baltic coastal dune grassland (grey dune)	B1.4a	VU	1904.8	8868.8	21.5

Permanent dystrophic waterbody	C1.4	NT	411214.1	1813359.0	22.7
Thermophile woodland fringe of base-rich soils	E5.2a	LC	129175.9	567204.5	22.8
Mediterranean tall perennial dry grassland	E1.3b	LC	587275.1	2572289.3	22.8
Subalpine moist or wet tall-herb and fern fringe	E5.5	LC	384870.2	1684939.0	22.8
Atlantic coastal Calluna and Ulex heath	B1.5b	LC	221.0	961.6	23.0
Mountain hay meadow	E2.3	VU	244487.7	1059128.7	23.1
Cryptogam- and annual-dominated vegetation on siliceous rock outcrops	E1.1b	VU	271623.5	1164224.8	23.3
Atlantic and Baltic moist and wet dune slack	B1.8a	VU	886.4	3772.5	23.5
Calcareous quaking mire	D4.1c	VU	48455.0	206164.3	23.5
Mediterranean wooded pasture and meadow	E7.3	NT	686966.3	2922362.1	23.5
Atlantic, Baltic and Arctic sand beach	B1.1a	VU	2966.2	12588.1	23.6
Mediterranean riparian scrub	F9.3	LC	377374.6	1572130.6	24
Oceanic to subcontinental inland sand grassland on dry acid and neutral soils	E1.9a	EN	395302.2	1635094.1	24.2
Temperate and submediterranean thorn scrub	F3.1e	LC	82601.8	341372.2	24.2
Lowland to montane temperate and submediterranean Juniperus scrub	F3.1a	LC	45834.2	188550.9	24.3
Cryptogam- and annual-dominated vegetation on calcareous and ultramafic rock outcrops	E1.1d	VU	258357.0	1049034.9	24.6
Inland sanddrift and dune with siliceous grassland	E1.9b	EN	106402.5	430030.6	24.7

Open Iberian supramediterranean dry acid and neutral grassland	E1.8	LC	32148.3	129865.8	24.8
Thermomediterranean scrub	F5.5	VU	9772.9	39286.4	24.9
Carpinus and Quercus mesic deciduous woodland	G1.Aa	NT	2411326.4	9690586.3	24.9
Alnus woodland on riparian and upland soils	G1.2a	LC	3256248.1	12945203.3	25.2
Western basiphilous garrigue	F6.1a	LC	136251.5	540347.4	25.2
Macaronesian thermophilous woodland fringe	E5.2c	NT	5237.2	20689.0	25.3
Mediterranean thermophilous deciduous woodland	G1.7b	LC	25290.2	99805.8	25.3
Atlantic and Baltic shifting coastal dune	B1.3a	NT	2212	8502.7	26
Base-poor spring and spring brook	C2.1a	VU	3447.7	13132.9	26.3
Mediterranean gypsum scrub	F6.7	LC	63594.3	240329.1	26.5
Fagus woodland on acid soils	G1.6b	NT	2270211.6	8517066.2	26.7
Supramediterranean garrigue	F6.6	LC	201863.1	755432.8	26.7
Iberian summer pasture (vallicar)	E2.4	NT	174191.9	651787.2	26.7
Temperate and boreal softwood riparian woodland	G1.1	NT	786686.7	2939867.1	26.8
Atlantic and Baltic coastal dune scrub	B1.6a	LC	703.3	2607.3	27
Mediterranean tall humid inland grassland	E3.1a	LC	285345.3	1057044.7	27
Mediterranean halo-nitrophilous scrub	F6.8	LC	127384.6	461629.6	27.6
Broadleaved swamp woodland on non-acid peat	G1.4	VU	275683.5	997362.5	27.6

Temperate subalpine Larix, Pinus cembra and Pinus uncinata woodland	G3.2	NT	324661.6	1168217.4	27.8
Central Mediterranean mountain hedgehog-heath	F7.4b	LC	14499.1	51075.1	28.4
Pemanent non-tidal, fast, turbulent watercourse of montane to alpine regions with mosses	C2.2a	LC	6266.4	22064.1	28.4
Arctic-alpine calcareous grassland	E4.4a	LC	185587.2	645067.0	28.8
Underground standing and running waterbody	C6.1	DD	63327.1	219440.0	28.9
Mediterranean closely grazed dry grassland	E1.3a	LC	283514.3	981009.7	28.9
Boreal and arctic acidophilous alpine grassland	E4.3a	LC	66750.8	230477.3	29
Permanent oligotrophic waterbody with very soft-water species	C1.1a	NT	200024.1	682394.2	29.3
Temperate inland salt marsh	E6.3	EN	21380.4	72841.5	29.4
Aapa mire	D3.2	LC	228843.2	778944.0	29.4
Temperate and boreal hardwood riparian woodland	G1.2b	EN	935850.3	3104986.1	30.1
Boreal ultramafic inland cliff	H3.2e	DD	720.7	2390.7	30.1
Fagus woodland on non-acid soils	G1.6a	NT	2871274.2	9479114.1	30.3
Ravine woodland	G1.Ab	NT	1666626.1	5499947.5	30.3
Pannonian and Pontic sandy steppe	E1.1a	CR	33552.0	110396.5	30.4
Temperate and continental Pinus sylvestris woodland	G3.4a	NT	354063.5	1161334.3	30.5
Corylus avellana scrub	F3.1g	LC	19439.7	63681.3	30.5
Submediterranean pseudomaquis	F5.3	LC	153905.5	500573.5	30.7
Mediterranean evergreen Quercus woodland	G2.1	LC	2065388.0	6675877.8	30.9

Permanent non-tidal, smooth-flowing watercourse	C2.3	NT	308999.8	997168.9	31
Temperate acidophilous alpine grassland	E4.3b	LC	165540.3	530991.5	31.2
Western acidophilous garrigue	F6.1b	LC	245405.4	783825.8	31.3
Temperate and submediterranean thermophilous deciduous woodland	G1.7a	LC	3200626.9	10132979.1	31.6
Mediterranean maquis and arborescent matorral	F5.1	LC	449540.1	1413916	31.8
Unvegetated or sparsely vegetated shore with mobile sediments in montane and alpine regions	C3.5d	VU	116149.9	363901.8	31.9
Mediterranean and Macaronesian riparian woodland	G1.3	VU	1812163.9	5677303.1	31.9
Arctic-alpine rich fen	D4.2	VU	3215.4	10042.8	32
Mediterranean annual-rich dry grassland	E1.3c	NT	31551.6	98097.9	32.2
Mediterranean to Atlantic open, dry, acid and neutral grassland	E1.A	VU	13218.2	41063.3	32.2
Atlantic and Baltic coastal Empetrum heath	B1.5a	VU	388.3	1205.3	32.2
Olea europaea-Ceratonia siliqua woodland	G2.4	LC	209229.2	646535.2	32.4
Wet heath	F4.1	VU	321784.6	991780	32.4
Temperate mountain Picea woodland	G3.1a	LC	772260.2	2378563.3	32.5
Lowland to montane temperate and submediterranean genistoid scrub	F3.1c	LC	392601.9	1190469.0	33
Balkan-Anatolian submontane genistoid scrub	F3.1d	VU	1101.1	3334.2	33
Machair	B1.9	LC	273.3	827.6	33

Heavy-metal dry grassland of the Balkans	E1.1h	NT	10843.2	32435.0	33.4
Fjell field	H5.1a	NT	79546.5	229252.7	34.7
Poor fen	D2.2a	VU	374034.6	1075499.8	34.8
Intermediate fen and soft-water spring mire	D2.2c	VU	414915.3	1184091.6	35
Non-calcareous quaking mire	D2.3a	VU	379776.1	1083222.0	35.1
Mediterranean lowland to submontane Pinus woodland	G3.7	LC	617116.6	1745333.7	35.4
Mediterranean inland salt steppe	E6.1	VU	44948.9	126449.8	35.5
Salix fen scrub	F9.2	NT	39883.5	111850.1	35.7
Iberian oromediterranean siliceous dry grassland	E1.5a	NT	36072.2	100569.9	35.9
Western Mediterranean spiny heath	F7.1	LC	21148.5	58918.1	35.9
Mediterranean short moist grassland of mountains	E3.2b	LC	28836.0	79441.8	36.3
Black Sea broad-leaved coastal dune woodland, Dry heath	F4.2	VU	541574.8	1473926.1	36.7
Boreal and arctic siliceous inland cliff	H3.1a	LC	112774.8	302614.3	37.3
Madeiran oromediterranean siliceous dry grassland	E1.5e	CR	370.7	987.0	37.6
Atlantic and Baltic broad-leaved coastal dune woodland	B1.7a	LC	614.2	1621.6	37.9
Mediterranean and temperate volcanic field	H6.1	LC	2900.7	7524.4	38.6
Raised bog	D1.1	EN	159782.4	413443.3	38.6
Mediterranean short moist grassland of lowlands	E3.2a	LC	21535.7	55584.9	38.7
Atlantic and Baltic soft sea cliff	B3.4a	LC	106.2	273.1	38.9
Oceanic valley bog	D2.1	VU	11674.2	29904.1	39

Mediterranean siliceous inland cliff	H3.1d	LC	57566.0	147293.0	39.1
Eastern Mediterranean mountain hedgehog-heath	F7.4c	LC	99161.7	251919.3	39.4
Baltic coastal meadow	A2.5b	EN	984.0	2457.0	40
Mediterranean base-rich inland cliff	H3.2d	LC	197491.6	491474.1	40.2
Alnus cordata woodland	G1.Ba	DD	24396.4	60504.1	40.3
Mediterranean and Macaronesian coastal dune grassland (grey dune)	B1.4b	EN	6765.7	16464.6	41.1
Temperate mountain Abies woodland	G3.1b	NT	442357.1	1070732.1	41.3
Madeiran xerophytic scrub	F8.2	EN	964.0	2326.5	41.4
Mediterranean mountain Abies woodland	G3.1c	LC	97890.8	232786.9	42.1
Continental dry steppe	E1.2b	NT	219949.2	519740.9	42.3
Mediterranean mountain Betula and Populus tremula woodland on mineral soils	G1.9b	LC	75877.9	178440.0	42.5
Perennial rocky grassland of Central Europe and the Carpathians	E1.1g	LC	89619.7	210590.9	42.6
Dry steppic, submediterranean pasture of South-Eastern Europe	E1.1j	VU	41702	97901.1	42.6
Submediterranean moist meadow	E3.3	LC	31112.7	72713.5	42.8
Blanket bog	D1.2	NT	394306.3	912322.8	43.2
Vegetated snow patch	E4.1	VU	35459.0	81919.0	43.3
Tidal river, upstream from the estuary	C2.4	EN	2783.4	6356.2	43.8
Alpine and subalpine ericoid heath	F2.2a	LC	907711.3	2067660.4	43.9
Temperate and submediterranean montane Pinus sylvestris-Pinus nigra woodland	G3.4b	LC	380422.2	848682.9	44.8

Permanent oligotrophic to mesotrophic waterbody with soft-water species	C1.1b	LC	189781.3	416587.0	45.6
Eastern garrigue	F6.2	LC	34006.1	73906.3	46
Mediterranean and Black Sea sand beach	B1.1b	LC	14648.0	31829.0	46
Taxus baccata woodland	G3.9a	LC	58614.5	126626.2	46.3
Ilex aquifolium woodland	G2.6	LC	134029.6	288062.3	46.5
Mediterranean and Black Sea moist and wet dune slack	B1.8b	LC	2641.9	5597.0	47.2
Small-sedge base-rich fen and calcareous spring mire	D4.1a	EN	320456.3	676928.8	47.3
Mediterranean Cupressaceae woodland	G3.9b	LC	258505.1	544853	47.4
Subalpine Pinus mugo scrub	F2.4	LC	183102.3	380408.1	48.1
Mediterranean and Black Sea coastal salt marsh	A2.5d	NT	11460.3	23718.1	48.3
Unvegetated or sparsely vegetated shore with mobile sediments in the Mediterranean region	C3.5e	LC	9525.6	19484.7	48.9
Calcareous spring and spring brook	C2.1b	VU	35582.0	72749.5	48.9
Baltic coniferous coastal dune woodland	B1.7c	VU	512.5	1032.3	49.6
Mediterranean montane Pinus sylvestris-Pinus nigra woodland	G3.4c	LC	282088.5	564474.2	50
Canarian xerophytic scrub	F8.1	VU	57288.6	114349.6	50.1
Subalpine deciduous scrub	F2.3	LC	31256.2	62195.0	50.3
Mediterranean and Black Sea coastal shingle beach	B2.1b	LC	2086.3	4063.1	51.3
Temperate, lowland to montane base-rich inland cliff	H3.2c	LC	57284.1	111472.8	51.4

Permanent lake of glaciers and ice sheets	C1.7	VU	9915.6	19219.9	51.6
Alpine and subalpine calcareous grassland of the Balkan and Apennines	E4.4b	LC	61280.2	118040.2	51.9
Mesotrophic to eutrophic waterbody with vascular plants	C1.2b	NT	373996.2	711911.7	52.5
Tall-sedge bed	C5.2	VU	127040.4	241199.6	52.7
Mediterranean and Black Sea shifting coastal dune	B1.3b	VU	16948.5	31602.5	53.6
Tall-helophyte bed	C5.1a	LC	178412.6	330180.2	54
Temperate and boreal riparian scrub	F9.1	LC	751931.2	1387888.0	54.2
Alpine and subalpine Juniperus scrub	F2.2b	LC	97287.8	177420.5	54.8
Temperate and boreal mountain Betula and Populus tremula woodland on mineral soils	G1.9a	LC	607861.4	1107594.8	54.9
Black Sea coastal dune grassland (grey dune)	B1.4c	EN	11.0	20.0	55
Balkan subalpine genistoid scrub	F2.2c	LC	9689.3	17597.1	55.1
Iberian oromediterranean basiphilous dry grassland	E1.5b	LC	25936.8	46785.5	55.4
Temperate Rubus scrub	F3.1b	DD	2513.8	4498.6	55.9
Temperate high-mountain siliceous inland cliff	H3.1b	LC	291669.1	521236.9	56
Temperate high-mountain base-rich inland cliff	H3.2b	LC	252230.7	447554.9	56.4
Greek and Anatolian oromediterranean siliceous dry grassland	E1.5d	LC	38931.5	68273.8	57
Western Mediterranean mountain hedgehog-heath	F7.4a	LC	115294.7	201436.6	57.2

Cyrno-Sardean oromediterranean siliceous dry grassland	E1.5c	EN	4696.8	8205.6	57.2
Permanent oligotrophic to mesotrophic waterbody with Characeae	C1.2a	VU	231792.2	402423.3	57.6
Continental inland salt steppe	E6.2	VU	133084.6	230521.2	57.7
Macaronesian heath	F4.3	LC	28764.8	49373.8	58.3
Mediterranean and Black Sea coastal dune scrub	B1.6b	VU	10577.4	18115.3	58.4
Mediterranean and Balkan subalpine Pinus heldreichii-Pinus peuce woodland	G3.6	NT	35758.3	60842.5	58.8
Periodically exposed saline shore with pioneer or ephemeral vegetation	C3.5c	EN	11282.8	18932.1	59.6
Subarctic and alpine dwarf Salix scrub	F2.1	NT	66099.4	110118.4	60
Temperate ultramafic inland cliff	H3.2f	DD	637.0	1061.0	60
Mediterranean ultramafic inland cliff	H3.2g	DD	8319.3	13778.8	60.4
Boreal and arctic base-rich inland cliff	H3.2a	DD	93572.4	154331.0	60.6
Small-helophyte bed	C5.1b	NT	40369.1	65225.1	61.9
Mediterranean and Black Sea rocky sea cliff and shore	B3.1b	LC	42958.0	69051.8	62.2
Mediterranean coniferous coastal dune woodland	B1.7d	LC	2562.9	4043.1	63.4
Periodically exposed shore with stable, mesotrophic sediments with pioneer or ephemeral vegetation	C3.5b	VU	50479.3	79352.8	63.6
Macaronesian laurophyllous woodland	G2.3	VU	14052.0	22054.8	63.7
Limestone pavement	H3.5a	LC	99434.4	155428.7	64

Canarian mountain hedgehog-heath	F7.4d	LC	12380.9	19149.8	64.7
Boreal and arctic siliceous scree and block field	H2.1	LC	14875.3	22875.6	65
Tall-sedge base-rich fen	D4.1b	EN	89596.0	135025.8	66.4
Periodically exposed shore with stable, eutrophic sediments with pioneer or ephemeral vegetation	C3.5a	NT	149847.3	224200.0	66.8
Macaronesian Juniperus woodland	G3.9c	VU	9558.6	14288.5	66.9
Mediterranean and Black Sea soft sea cliff	B3.4b	DD	697.6	1029.6	67.8
Temperate temporary waterbody	C1.6a	LC	5084.7	7473.9	68
Temperate, lowland to montane siliceous inland cliff	H3.1c	LC	89526.7	130953.0	68.4
Macaronesian rocky sea cliff and shore	B3.1c	LC	1717.2	2495.9	68.8
Wet inland cliff	H3.4	DD	9496.1	13756.8	69
Mediterranean temporary waterbody	C1.6b	VU	44631.0	64272.9	69.4
Macaronesian inland cliff	H3.3	LC	12601.0	17979.5	70.1
Temperate high-mountain siliceous scree	H2.3	LC	92919.4	131759.7	70.5
Macaronesian heathy woodland	G2.7	VU	18631.9	26203.0	71.1
Palsa mire	D3.1	CR	36087.0	49550.8	72.8
Temperate high-mountain base-rich scree	H2.4	LC	89504.1	122634.5	73
Cave	H1.1	LC	79530.7	103745.0	76.7
Western Mediterranean base-rich scree	H2.6b	LC	36131.8	46253.1	78.1
Relict mire of Mediterranean mountains	D2.2b	VU	24.0	30.0	80
Temperate, lowland to montane base-rich scree	H2.6a	LC	14280.0	17800.7	80.2

Temperate, lowland to montane siliceous scree	H2.5	LC	8406.8	10178.6	82.6
Canarian Phoenix grove	G2.5b	VU	5568.7	6520.0	85.4
Snow pack	H4.1	VU	48210.3	56009.4	86.1
Ice cap and glacier	H4.2	VU	48210.3	56009.4	86.1
Boreal and arctic base-rich scree	H2.2	DD	3652.4	4242.4	86.1
Black Sea broad-leaved coastal dune woodland	B1.7b	EN	4303.5	4983.4	86.4
Pinus canariensis woodland	G3.8	LC	19548.6	22346.1	87.5
Permanent inland saline and brackish waterbody	C1.5	NT	10920.1	12108.9	90.2
Inland saline or brackish helophyte bed	C5.4	EN	17481.7	19316.9	90.5
Rock glacier and unvegetated ice-dominated moraine	H4.3	NT	12333.3	13446.1	91.7
Mediterranean montane Cedrus woodland	G3.4d	VU	4528.5	4901.5	92.4
Macaronesian coastal dune scrub	B1.6c	EN	370.3	388.6	95.3
Eastern Mediterranean base-rich scree	H2.6c	LC	9285.6	9652.2	96.2

* *Estimated habitat type areas derived by the methodology described in Appendix I.*

II

Evaluating and expanding the European Union's protected-area network toward potential post-2020 coverage targets

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Abstract. The Convention on Biological Diversity's (CBD) strategic plan will expire in 2020, but biodiversity loss is ongoing. Scientists call for more ambitious targets in the next agreement. The nature-needs-half movement, for example, has advocated conserving half of Earth to solve the biodiversity crisis, which has been translated to protecting 50% of each ecoregion. We evaluated current protection levels of ecoregions in the territory of one of the CBD's signatories, the European Union (EU). We also explored the possible enlargement of the Natura 2000 network to implement 30% or 50% ecoregion coverage in the EU member states' protected area (PA) network. Based on the most recent land-use data, we examined whether ecoregions have enough natural area left to reach such high coverage targets. We used a spatially explicit mixed integer programming model to estimate the least-cost expansion of the PA network based on three scenarios that put different emphasis on total conservation cost, ecological representation of ecosystems or emphasize an equal share of the burden among member states. To realize 30% and 50% ecoregion coverage, the EU would need to add 6.6% and 24.2%, respectively, of its terrestrial area to its PA network. For all three scenarios, the EU would need to designate most recommended new PAs in seminatural forests and other semi- or natural ecosystems. Because 15 ecoregions did not have enough natural area left to implement the ecoregion-coverage targets, some member states would also need to establish new PAs on productive land, allocating the largest share to arable land. Thirty percent ecoregion coverage was met by protecting remaining natural areas in all ecoregions except three, where productive land would also need to be included. Our results support discussions of higher ecoregions protection targets for post-2020 biodiversity frameworks.

Keywords: Aichi targets, conservation targets, ecological representation, Half-Earth, mixed integer programming, nature-needs-half, protected-area networks, systematic conservation planning

1. Introduction

The Convention on Biological Diversity's (CBD) Strategic Plan for Biodiversity 2011-2020 will soon expire. However, the international community has not reached its goal of halting biodiversity loss. At COP14, the CBD's signatories discussed the global post-2020 biodiversity framework and considered the strategic expansion of protected areas (PAs) as an essential measure toward the 2050 biodiversity vision to live "in harmony with nature" (UNEP 2011).

Current PA-coverage targets of Aichi Target 11 (i.e., protecting 17% of the global terrestrial area and 10% of the marine area by 2020) are too low for adequate long-term protection of biodiversity (Baillie & Zhang 2018). Proposals for the CBD's next strategic plan range from conserving 100% of all remaining intact ecosystems (Watson et al. 2018) to protecting 30% of all land and ocean areas until 2030 and 50% until 2050 (Baillie & Zhang 2018). The nature-needs-half or Half-Earth movement argues that 85% of the species on Earth could be sustained if half the planet is set aside as "inviolable natural reserves" (Wilson 2016), a goal that has been translated to protecting 50% of each of the world's ecoregions (Dinerstein et al. 2017a). There has been much support for this vision among the conservation science community (Cafaro et al. 2017; Watson & Venter 2017; Kopnina et al. 2018), and some researchers have examined its systematic implementation and possible trade-offs with other land uses on the global level (Mehrabi et al. 2018; Pimm et al. 2018). However, other scientists warn there is not yet enough scientific evidence to back the Half-Earth vision (Sleep et al. 2017) or challenge its feasibility (Büscher et al. 2017). One unquestionable strength of Half-Earth is its simplicity, transferring a clear goal that is similar to the 2 °C target of the Paris Agreement to limit climate change. Formulating a similar target for biodiversity protection could facilitate and stimulate more ambitious actions (Mace et al. 2018). Because signatories explicitly call for scenarios and models on different spatial scales to inform the development of post-2020 targets (CBD 2018), we undertook a detailed assessment for the European Union (EU) as one of the signatories of the CBD.

Europe has a high population density, a long history of human land use, and little wilderness left (McCloskey & Spalding 1989). With 22.7% of the 11,260 European species on the IUCN Red List classified as threatened (IUCN 2017), the EU will fail to stop biodiversity loss by 2020 (Hochkirch et al. 2013). Despite missing the overall target, the EU made substantial progress in achieving some of CBD's Aichi targets. The EU created the world's largest network of protected areas, Natura 2000, in an exemplary effort (Campagnaro et al. 2019). With 18.2% of the terrestrial area under formal protection, Natura 2000 exceeds the 17% PA coverage target of Aichi Target 11 (European Commission 2018). Considering also nationally designated PAs that are not part of Natura 2000, more than 26.3% of the EU's terrestrial area is already protected (UNEP-WCMC and IUCN 2019). Therefore, the EU considers its terrestrial

Natura 2000 network nearly complete (Orlikowska et al. 2016). However, neither the EU's terrestrial (Müller et al. 2018) nor the marine (European Environment Agency 2018b) PA network is fully ecologically representative, and visions such as Half-Earth would require adopting more ambitious PA-coverage targets. Furthermore, many sites lack appropriate management (Hochkirch et al. 2013) and include land under intense human pressure, which leads to an overestimation of the actual level of protection (Jones et al. 2018). Other challenges that hamper successful biodiversity protection in the EU are small PA size and landscape fragmentation, extinction debts, and climate change (Gaston et al. 2008).

We aimed to evaluate the current amount of ecoregions protected in the entire terrestrial PA estate of the EU's member states and to assess how the EU could fill potential gaps toward more ambitious 30% and 50% ecoregion coverage targets. First, we determined which ecoregions have not reached such targets yet. Second, we used the latest European land-cover data to analyze whether there would be enough natural areas left to protect 30% and 50% of the ecoregions or whether the inclusion of productive land (arable land, productive grassland, and production forest) would be necessary. Third, we simulated how the EU could expand its terrestrial Natura 2000 network cost-effectively to implement the 30% or 50% ecoregion-coverage target within its member states' entire network of PAs. Finally, we tested two further scenarios to account additionally for the ecological representation of ecosystems and for sharing the burden of PA designation more equally among member states.

2. Methods

2.1 Study region and data sources for modeling

We examined the terrestrial area of all 28 EU member states, excluding territories outside the Palearctic realm. We also excluded the Azores and Madeira because of data deficiencies.

We considered 41 ecoregions (Fig. II.1 and II.2) from the Ecoregions 2017 Resolve map (Dinerstein et al. 2017b) to assess the representation of these broad but ecologically distinct regions as primary biodiversity surrogates for the EU's PA network. To evaluate how much natural area is left to fill gaps in ecoregion coverage, we used the latest CORINE land-cover assessment (European Environment Agency 2018a). We excluded marine and anthropogenic land-cover classes and reclassified the remaining into semi- or natural ecosystems and productive land (Supplementary, Table II.S1). We refined the three CORINE forest classes (3.1.1. broad-leafed, 3.1.2 coniferous, and 3.1.3 mixed) with data from the Forest Management Map of European Forests (Hengeveld et al. 2012). We considered the classes nature reserve, close to nature, and combined objective as seminatural forests. Even-aged forestry and short-rotation forestry were considered intensively managed production forests. We split each CORINE forest class into two, containing production forests and seminatural forests. In total, semi- or natural ecosystems included 18 land use classes, which we grouped into seminatural forest, natural grassland, and other semi- or natural ecosystems for reporting our results. Productive land included 14 land use classes, which we divided into production forests, productive grassland, and arable land. To further enhance ecological representation, we used the semi- or natural ecosystems as secondary biodiversity surrogates in our expansion exercise.

We took into account data on Natura 2000 sites (DG ENV 2017) and nationally designated PAs from the World Database on Protected Areas (UNEP-WCMC and IUCN 2019). We prepared the WDPA dataset according to the guidelines of the UN Environment Program - World Conservation Monitoring Centre (UNEP-WCMC 2019). We used both data sets to calculate PA coverage of ecoregions, semi- or natural ecosystems, and productive land categories within the EU.

We used land opportunity costs as the best available proxies for conservation costs. Systematic conservation planning exercises need to include all relevant costs of conservation to find cost-efficient solutions (Naidoo et al. 2006). However, costs on reserve establishment and management of PAs are currently not available at the EU level, and it is not straightforward to estimate them from existing data (Kotiaho & Moilanen 2015). We estimated land opportunity costs based on agricultural land rent data on NUTS-2 level (Farm Accountancy Data Network 2018). We calculated arithmetic means from annual data from 2009 to 2015 (Supplementary, Table II.S2). We created the 499 planning units (PUs) used in the modeling system by intersecting ecoregions and NUTS-2 regions.

2.2. Representation metrics

To evaluate ecological representation in the PA network, we applied the metrics mean target achievement (MTA, Jantke et al. 2019) and protection equality (PE, Chauvenet et al. 2017). The MTA metric showed to which degree ecoregions already meet the 30% or 50% coverage target. The metric's values range from 0% (no ecoregion is protected) to 100% (all ecoregions fulfill the target). We used the R package ConsTarget to calculate this metric (Jantke et al. 2018). The PE metric explores how homogenously PA networks cover biodiversity features, such as species or habitats. This metric also ranges from 0% (heterogeneous representation of biodiversity features) to 100% (representation of biodiversity features is perfectly homogeneous). We used the R package ProtectEqual (Chauvenet et al. 2015) to calculate how homogenously the PA network represented semi- or natural ecosystems. We computed the same metric to compare how homogenously the PA network covered the member states' territories

We calculated both metrics for the current PA network and the simulated optimal networks for the 30% and 50% ecoregion-coverage target and each scenario.

2.3 Scenarios

To compare how different emphasis on total cost of conservation, ecosystem representation, or member state equity could change the designated additional conservation areas of the modeled network expansion, we developed three scenarios. In the first scenario, cost only, we simulated a least-cost network expansion that only fulfilled an ecoregions' coverage target. In the second scenario, ecosystem equity, we simulated a least-cost expansion to fulfill the ecoregion-coverage target while aligning the protected proportions of semi- or natural ecosystems (serving as a second biodiversity surrogate) as much as possible. For the third scenario, member state equity, we simulated a least-cost network expansion to fulfill the ecoregion-coverage targets while aligning protected proportions of member states as much as possible. We compared total cost, ecosystem protection equality, and member-state protection equality for all three scenarios.

2.4 Simulation of systematic network expansion

We modified the linear programming modeling system from Müller et al. (2018) to estimate the least-cost expansion of the EU member states' PA network to reach 30% and 50% ecoregion coverage targets. The modeling system consisted of two consecutive models that we solved with mixed-integer programming. For the cost-only scenario, we solved only the second model. For the other scenarios, both models were solved consecutively. The first model determined the required additional conservation area for closing coverage gaps in ecoregions while increasing protection equality of semi- or natural ecosystems or member states as much as possible. The second model allocated these additional conservation areas to the cheapest set of PUs. In adjusting the model from Müller et al. (2018) to this study, we changed the following: productive land could be part of the additional conservation areas if and only if an ecoregion did not have sufficient unprotected semi- or natural ecosystem area for meeting a given coverage target. Appendix II contains a detailed model description.

3. Results

3.1 Current representation of ecoregions, land-cover classes, and member states

The EU's current PA network covered 30% of 26 ecoregions. It also covered 50% of nine ecoregions, but these were typically rather small (Figs. II.1 & II.2A). Inherently, the protection of many ecoregions in the entire PA network was considerably higher than protection through Natura 2000 sites alone. For example, the United Kingdom designated only a minority of PAs as Natura 2000 sites for the British ecoregion England lowlands beech forests. Iberian coniferous forests, however, received nearly all protection through Natura 2000 sites (Fig. II.2A).The MTA metric revealed that the

EU is already quite close to reaching the 30% ecoregion-coverage target with its PA network and has also achieved the 50% ecoregion-coverage target by half (Table II.1).

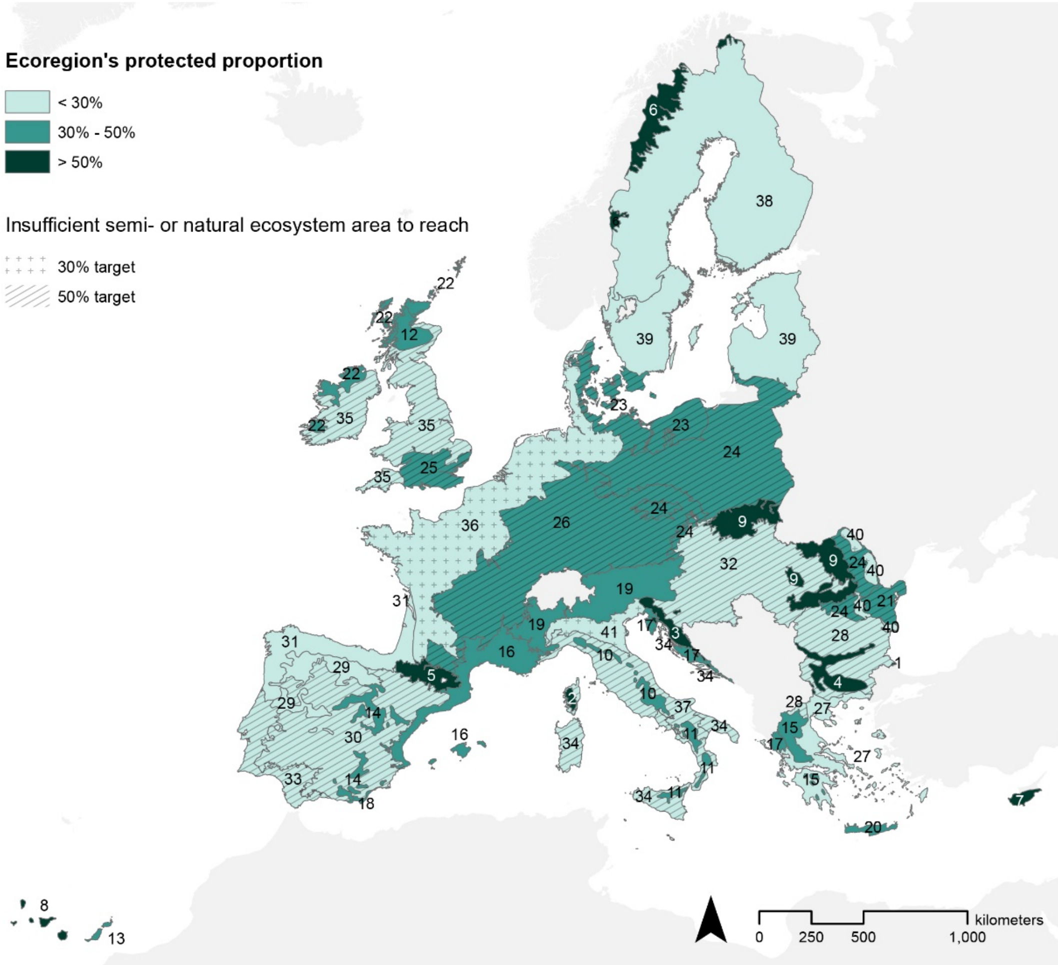

Figure II.1 *Current ecoregion protection levels in EU member states' protected area network (ecoregion numbers correspond to Fig. II.2).*

Current ecosystem representation levels ranged from 27% for transitional woodland and shrub to 94% for coastal salt marshes (Supplementary, Table II.S1). The high PE value (Table II.1) indicated that even though the range between the lowest and highest protection level was large, ecosystem protection levels within the PA network were overall already quite equal. Existing PAs notably also included productive land (Fig. II.2B). Land use intensity on productive land is presumably still high, potentially decreasing PA effectiveness for biodiversity conservation. Although the current PA network also covered member states already quite homogenously (Table II.1), Ireland protected only 14% of its terrestrial territory while Cyprus and Slovenia conserved 54%. Together with Luxemburg, these three member states established a Half-Earth extent for their national PA networks.

Table II.1 Comparison of protection levels, mean target achievement, protection equality of ecosystems and member states, and total conservation cost for the European Union's current protected area (PA) network and the three PA expansion scenarios.

	Current PA network	Network expansion					
		30 %			50%		
		cost-only	ecosystem equity	member state equity	cost-only	ecosystem equity	member state equity
Protected terrestrial proportion of the EU[a] (%)	26.3	32.6			50.3		
Terrestrial EU[a] area added to the network (km²)	-	283,902.4 (6.6 %)			1,050,986.0 (24.2 %)		
Ecoregion MTA[b] for the 30% target (%)	88.2	100.0			-		
Ecoregion MTA[b] for the 50% target (%)	68.5	-			100.0		
Ecosystem PE[c] (%)	78.0	87.0	88.3	86.9	94.7	97.5	94.6
Member state PE[c] (%)	76.2	79.4	81.9	85.0	83.0	85.3	95.2
Additional land opportunity cost (billion €/year)	-	2,710.6	3,739.6	3,887.8	12,559.0	13,788.9	14,648.8

[a] European Union.

[b] Mean target achievement.

[c] Protection equality.

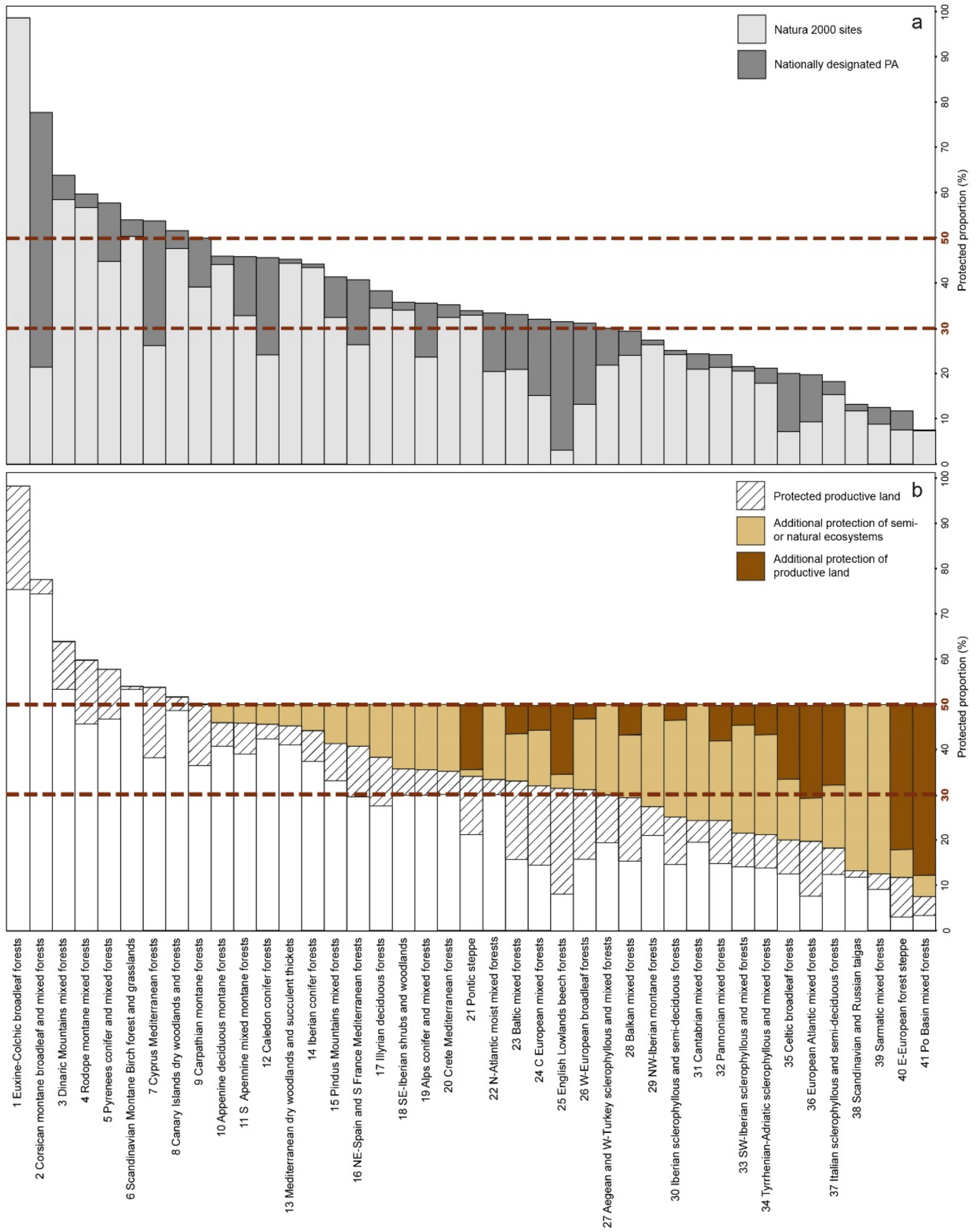

***Figure II.2** (a) Current ecoregion protection levels in EU member states' protected area (PA) network and (b) needed additional protection area of semi- or natural ecosystems and production land to reach the 30% or 50% ecoregion coverage target.*

3.2 Remaining natural area for implementation of ecoregion-coverage targets

There was not enough semi- or natural ecosystem area left in the EU to reach the coverage targets for all ecoregions (Fig. II.2B). Among the ecoregions falling short of 30%, there was not enough semi- or natural ecosystem area to achieve targets in Po Basin mixed forests, East European forest steppe, and European Atlantic mixed forests (Fig. II.1). Thus, member states containing part of these ecoregions would need to set productive land aside. Similarly, the EU would need to include productive land in the PA network in 15 ecoregions to implement the 50% ecoregion-coverage target. Notably, the majority of ecoregions with the lowest amount of protection did not have enough semi- or natural ecosystem areas left to implement the protection targets (Fig. II.2B). For example, Italy protected only 8% of Po Basin mixed forests, and the remaining natural area would not even be sufficient to raise the protection level to 15%.

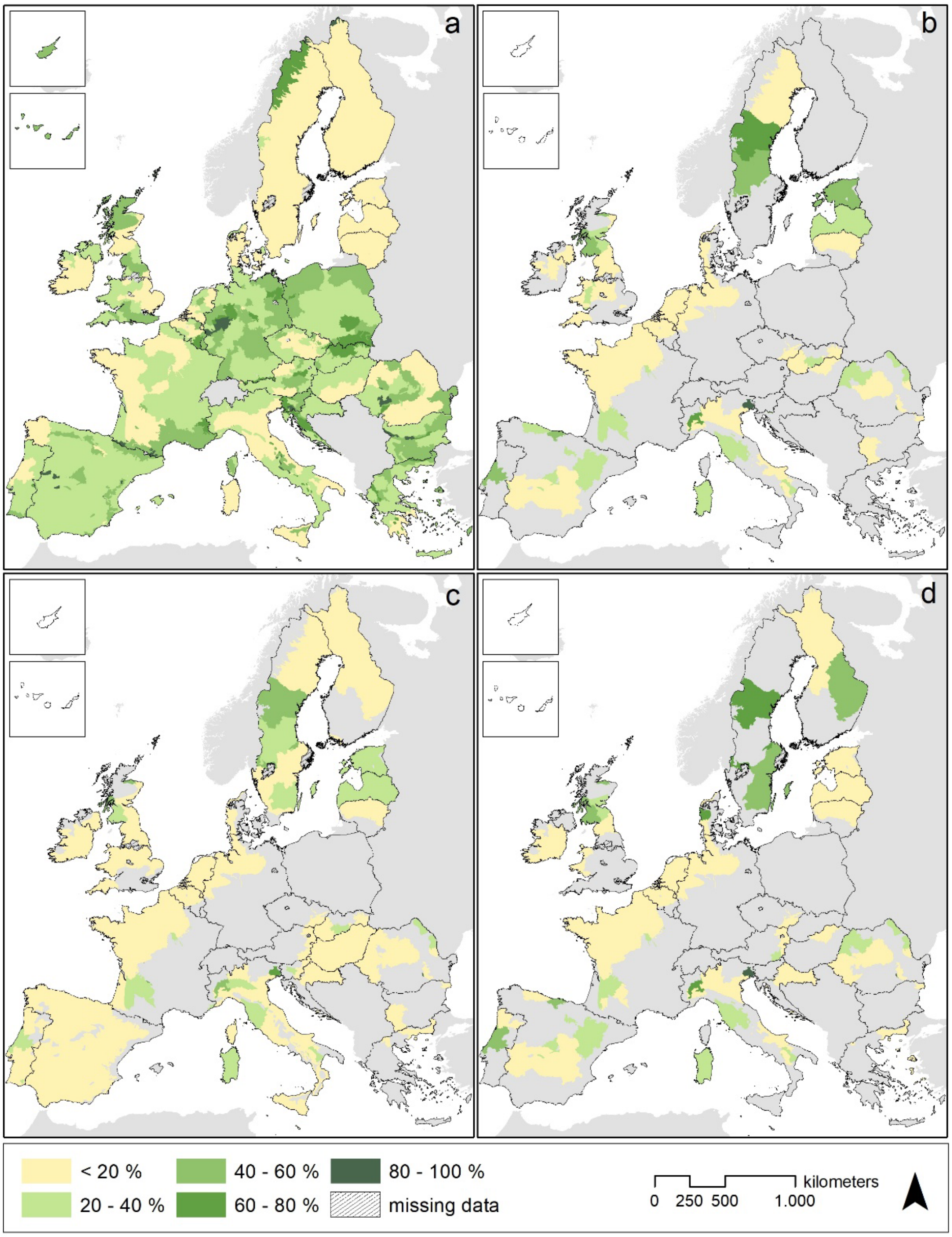

Figure II.3 *Percent area (a) currently protected in each EU planning unit (excludes CORINE artificial surfaces) and required additional percent protected area for the (b) cost-only, (c) ecosystem equity, and (d) member state equity scenarios for the 30% ecoregion coverage target.*

3.3 Scenarios of network expansion

While the EU would need to add only a small fraction of its total territory to the PA network to achieve 30% ecoregion coverage, nearly one-quarter of the EU territory would need to be added to reach 50% ecoregion coverage (Table II.1). The three scenarios exemplarily visualize potential trade-offs between total conservation cost and the distribution of additional conservation areas across ecosystems and member states.

Not surprisingly, when only minimizing total conservation cost (cost-only scenario), additional conservation areas for a gap ecoregion concentrated on a few PUs with comparably low-cost values (Fig. II.3B). Furthermore, this scenario yielded the lowest increases in ecosystem and member state PE (Table II.1). Accounting for a distribution of PA that is as even as possible across ecosystems (ecosystem equity scenario) led to higher total conservation cost than the cost-only scenario (Table II.1), but yielded higher ecosystem and member state PE values (Table II.1) and a more even allocation of additional PAs across PUs (Fig. II.3C). Finally, accounting for a distribution of PA that is as even as possible across member states (member state equity scenario) yielded the most expensive network enlargement (Table II.1). While member state equity generated ecosystem PE values similar to the cost-only scenario, it resulted in the highest member state PE values (Table II.1). The distribution of PAs across PUs was more concentrated than in the ecosystem equity scenario, indicating that increasing the protected amount of currently underrepresented ecosystems was a stronger constraint to the algorithm than increasing the protection levels of currently less protected member states (Fig. II.3D). The PE values did not reach 100% in any scenario because the representation of ecosystems and member states showed a wide range in the current PA network (Supplementary, Table II.S1, Table II.S3, Fig. II.S4.1 & Fig. II.S4.2).

3.4 Land use category and member state contribution

Seminatural forest would contribute most to an extended PA network for both ecoregion coverage targets and all three scenarios, followed by other semi- or natural ecosystems and arable land (Fig II.4). While there were only slight differences between the three scenarios at the EU level, changes were more apparent on the member state level. For example, the amount of seminatural forest area Sweden would need to set aside differed remarkably for the three scenarios, whereas for other member states, such as Germany and France, it stayed roughly the same (Supplementary, Fig II.S5). Most member states would need to protect considerable proportions of their natural areas, whereas large parts of productive lands could remain unprotected.

Member-state protection levels within the potential future PA network extents varied among the three scenarios (Supplementary, Fig. II.S4.1 & Fig. II.S4.2), as did the additional protection area in each PU within a member state (Fig. II.3 and Supplementary, Fig. II.S6). For the cost-only scenario, we found very high protection levels in member states with comparably low land rent prices. For example, Slovakia would have to protect 81% of its terrestrial territory for the 50% ecoregion coverage target. The member state equity scenario, in contrast, forced the algorithm to allocate additional PAs also to member states with relatively high land rents, such as Finland and Denmark.

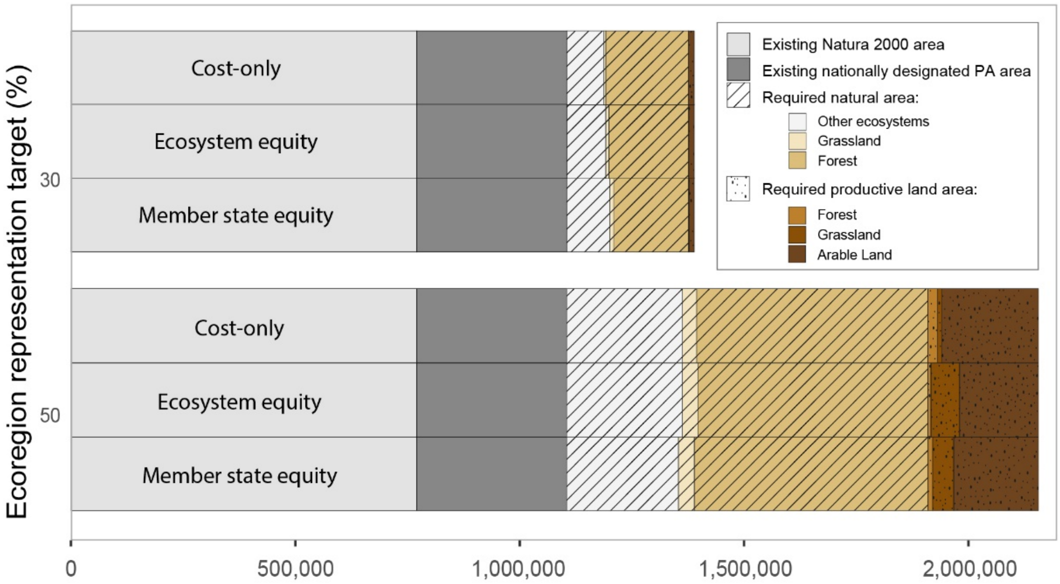

Figure II.4 Existing and required protected area (PA) for both EU ecoregion coverage targets and all three scenarios (cost-only, ecosystem equity, and member state equity).

4. Discussion

Biodiversity loss in Europe is continuing despite all past conservation efforts and it will keep continuing unless European countries adopt even more ambitious policies (IPBES 2018). Encouragingly, more than half of all European ecoregions reached 30%, and nine ecoregions even achieved 50% coverage in the EU member states' current PA network. Furthermore, only a few ecoregions did not have enough unprotected semi- or natural ecosystem areas left to achieve 30% or 50% protection. However, previous studies show that the Natura 2000 network still underrepresents European biodiversity (e.g., narrow-ranged species [Gruber et al. 2012; Abellán & Sánchez-Fernández 2015] and amphibians and reptiles [Maiorano et al. 2015; Sánchez-Fernández & Abellán 2015]). If the EU would systematically expand the Natura 2000 network, additional PAs could not only close the gaps in ecoregion coverage we found, but also increase the size and connectivity of existing PAs, benefitting, for example, insect species (Habel et al. 2019), species with large home ranges (Jantke et al. 2011), and species shifting their distribution due to climate change (Santini et al. 2016).

The model allocated the majority of additional PAs for all three scenarios to seminatural forests, followed by other semi- or natural ecosystems and arable land. While forests used to be natural, self-sustaining ecosystems in Europe for millennia (Mai 1989), many of the forest types listed on Annex I of the Habitats Directive have evolved during the last centuries as extensively used silvicultural systems. Natura 2000 regulations allow continued commercial use of forests, but in many cases restrict this use to close-to-nature forestry (Sotirov 2017). Land users might already manage many forests of our seminatural forest category in compliance with favorable conservation statuses of Natura 2000 forest types. However, a detailed assessment of the economic implications of protecting large forest areas within the EU is needed.

For further seminatural ecosystems (e.g., peatlands, freshwater ecosystems, and heaths), the proposed expansion would be an important step toward conserving remaining ecosystems as called for by Watson et al. (2018). Many of these ecosystems are currently not in good ecological condition in the EU (European Environment Agency 2015). Protecting them might help prevent further damage and facilitate restoration efforts.

High ecoregion-coverage targets would also require the inclusion of arable land in some member state PA networks. Possible management options for these new PAs include traditional restoration approaches to convert arable land into seminatural ecosystems, such as extensively used grasslands (Verhagen et al. 2001). Furthermore, rewilding as a low-cost management strategy for abandoned farmland (Ceauşu et al. 2015) could enable redevelopment into predominantly nature-shaped ecosystems, such as natural forests (Van Uytvanck et al. 2010).

Including not only Natura 2000 sites in our analysis, but also all PA categories reported to the WDPA provided a more realistic picture of the coverage of many ecoregions. However, not all other PA categories strictly aim at biodiversity conservation; thus, their effectiveness to support local biodiversity may be lower than expected. The same constraint may even apply to Natura 2000 areas because not all sites have comprehensive management plans (European Environment Agency 2015). We found a proportion of the current PA network in each ecoregion on productive land, where land use intensity may be too high for effective biodiversity conservation. For a PA network to effectively protect biodiversity, it does not suffice to create and maintain "paper parks" (Barnes et al. 2018). Thus, the EU member states should adopt adequate restoration and management measures, both for the already existing and for the newly designated PAs.

Despite the urgent need to act on the biodiversity crisis and better safeguard European biodiversity, the EU and its member states would face many challenges if they opted for further expansion of the Natura 2000 network. First, it is still uncertain how high conservation targets would need to be to stop biodiversity loss (Sleep et al. 2017). We, therefore, decided to define two potential targets based on Dinerstein et al.'s (2017a) operationalization of the Half-Earth vision. These targets are measurable with available metrics and data. Second, a crucial question for the EU and its member states is who would have to protect what. We proposed searching for the optimal solution at the EU level when allocating new PAs, which yields a cost-effective expansion and a systematic increase in the ecoregion and ecosystem representation in the network. However, member states could be affected quite differently depending on the overall strategy the EU adopted, as we visualized by comparing three different expansion scenarios. While the cost-only scenario offered the cheapest solution at EU level to close the gaps in ecoregion coverage, it tended to allocate most additional conservation areas to so-called cheap member states and PUs, a strategy that could be perceived as rather unfair by affected regions or member states. Therefore, the member state equity scenario, aligning the protection levels of member states, yielded a strategy in which member states share the burden of nature protection more equally, but which implies additional costs on the EU level. Third, there is little doubt that the establishment of more PAs may decrease the area for intensive agricultural and forestry production in the EU.

Assessing the economic losses that could result from achieving higher ecoregion-coverage targets was beyond the scope of our study, but should be the subject of future research. Landowners and users have frequently resisted the designation of Natura 2000 sites (Hiedanpää 2002; Welch-Devine 2011; Kati et al. 2015). To raise acceptance for more PA designations among affected stakeholders, positive incentives (Rojas-Briales 2000; Anthon et al. 2010) and bottom-up participatory designation processes (Rauschmayer et al. 2009) could help. Finally, the EU should also scrutinize the effects of higher PA coverage in its territory on global land use patterns (Lotze-Campen et al. 2018). From a global conservation perspective, there is the danger of saving European biodiversity at the expense of increasing pressure on biodiversity elsewhere on the planet. However, recent studies at European (Zech & Schneider 2019) and global levels (Springmann et al. 2018) indicate substantial environmental benefits if EU citizens would decrease their current consumption levels of agricultural products (e.g., reduce meat consumption).

Our modeling exercise is subject to several limitations. First, our reported land opportunity cost values are only rough estimates of the overall conservation costs and may vary considerably from true costs because we could not include restoration or management cost. Furthermore, we compared ecosystems on a rather broad classification level. Based on CORINE data, we could only include 18 semi- or natural ecosystem classes in our analysis, whereas Annex I of the Habitats Directive lists more than 230 habitat types. While data sets with a finer ecosystem classification, such as the European Red List of habitat types exist, data deficiencies and missing data did not allow us to use them.

Our study provides the first EU-scale assessment on increasing ecoregion-coverage targets toward 30% or even 50% in the PA network. Based on recent land use data, we identified ecoregions with sufficient natural areas left to reach such high targets theoretically. For all three of the scenarios we explored, our results suggested that most new PAs would need to be designated in seminatural forests, followed by other semi- or natural ecosystems and arable land. Our results show possible pathways for implementing more ambitious conservation targets in the EU, which should be complemented by a thorough land use sector analysis to evaluate potential economic implications. With these results, our study provides valuable insights to inform debates for the CBD's and consequently also the EU's post-2020 biodiversity framework.

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Appendix II

We modified and further developed the modeling system from Müller, Schneider, and Jantke (2018) to simulate Natura 2000 enlargements under three alternative land allocation scenarios: 'cost-only', 'ecosystem equity', and 'member state equity'. The modeling system consists of two linked allocation models that we describe in detail here (Fig. II.A1). The mathematical representation includes sets, variables, parameters, equations, and mathematical operators. Sets are indexes of variables, parameters, and equations, which we denote by subscripts. Here we use sets to depict planning units $p = \{p_1,\ldots,p_{499}\}$, ecoregions $e = \{e_1,\ldots,e_{41}\}$, natural and semi-natural ecosystems $n = \{n_1,\ldots,n_{18}\}$, agricultural or forestry production land types $a = \{a_1,\ldots, a_{14}\}$, European member states $\mathrm{m} = \{\mathrm{m}_1,\ldots,\mathrm{m}_{28}\}$, and protection states $\mathrm{s} = \{\mathrm{s}_0$ (unprotected), s_1 (protected)$\}$. We use an iteration index $i = \{i_1,\ldots,i_k\}$ to perform a sequence of model solutions for the distribution objectives of the 'ecosystem equity' and 'member state equity' scenarios. Capital letters denote variables. The variable L is the objective variable for allocation model 1 and depicts the lowest representation of natural and semi-natural ecosystems. The non-negative variable array R depicts the representation of natural and semi-natural ecosystems *n* in the PA network. The non-negative variable array A represents the additional conservation area required for ecosystem *n* or production land type *a* in member state *m* and ecoregion *e*. The binary variable I is an auxiliary variable and indicates whether natural and semi-natural ecosystems in an ecoregion are fully protected (I=1) or not (I=0).

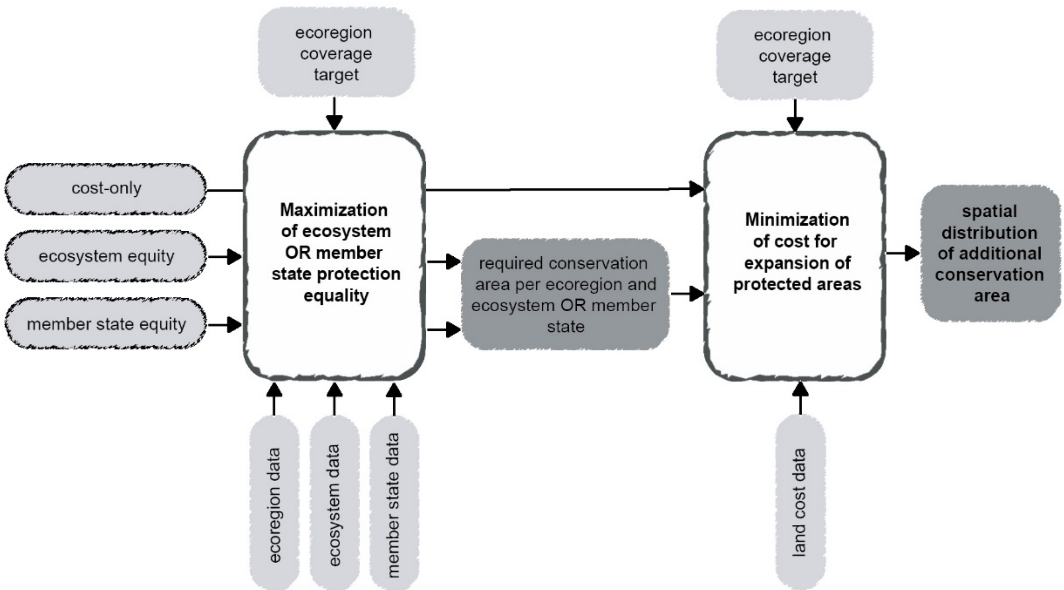

Figure II.A1 *Overview of modeling approach. Light grey boxes with dark fringes depict the scenarios, light grey boxes depict input data, and dark grey boxes output data and white boxes with dark fringes show analysis tools.*

The variable O is the objective variable for the allocation model 2 and denotes total land value summed over all additionally selected protected areas. The non-negative variable array Y depicts additional conservation area of ecosystem *n* or production land type *a* in planning unit *p* and ecoregion *e*. The parameter c depicts the agricultural land rent in planning unit *p*. Furthermore, the parameter u depicts the area of ecoregion *e* with protection state *s* and v depicts the area of ecosystem *n* or production land type *a* in planning unit *p*, member state *m* and ecoregion *e* with protection state *s*. t is the ecoregion representation target.

Allocation model 1: Homogenous alignment of semi- or natural ecosystems' protected proportions

$$Maximize \ \ L_i \qquad \forall i\big|_{n_i \neq \{\}} \qquad [1]$$

$$L_i \leq R_n \qquad \forall i, n \in n_i \qquad [2]$$

$$u_{e,s_1} + \sum_{m,n} A_{m,e,n} + \sum_{m,a} A_{m,e,a} = t_e \cdot \sum_{s} u_{e,s} \qquad \forall i,e \qquad [3]$$

$$A_{m,e,n} \leq \sum_{p} v_{m,p,e,n,s_0} \qquad \forall i,m,e,n \qquad [4]$$

$$A_{m,e,a} \leq \sum_{p} v_{m,p,e,a,s_0} \qquad \forall i,m,e,a \qquad [5]$$

$$R_n = \frac{100 \cdot \sum_{m,e} \left(A_{m,e,n} + \sum_{p} v_{m,p,e,n,s_1} \right)}{\sum_{m,p,e} \left(v_{m,p,e,n,s_0} + v_{m,p,e,n,s_1} \right)} \qquad \forall i,n \qquad [6]$$

$$\sum_{m,a} A_{m,e,a} - I_e \cdot \sum_{m,p,a} v_{m,p,e,a,s_0} \leq 0 \qquad \forall i,e \qquad [7]$$

$$-\sum_{m,n} A_{m,e,n} + I_e \cdot \sum_{m,p,n} v_{m,p,e,n,s_0} \leq 0 \qquad \forall i,e \qquad [8]$$

$$A_{m,e,n} = A^{*}_{m,e,n} \qquad \forall i > 1, m,e,n \notin n_i \qquad [9]$$

$$A_{m,e,a} = A^{*}_{m,e,a} \qquad \forall i > 1, m,e,a \notin a_i \qquad [10]$$

Allocation model 2: Cost-efficient expansion of protected areas

$$Minimize\ \ O = \sum_{m,p}\left(c_p \cdot \left(\sum_{e,n} Y_{m,p,e,n} + \sum_{e,a} Y_{m,p,e,a}\right)\right) \qquad [11]$$

$$Y_{m,p,e,n} \le v_{m,p,e,n,s_0} \qquad \forall m,p,e,n \qquad [12]$$

$$Y_{m,p,e,a} \le v_{m,p,e,a,s_0} \qquad \forall m,p,e,a \qquad [13]$$

$$\sum_{p} Y_{m,p,e,n} = A^{*}_{m,e,n} \qquad \forall m,e,n \qquad [14]$$

$$\sum_{p} Y_{m,p,e,a} = A^{*}_{m,e,a} \qquad \forall m,e,a \qquad [15]$$

$$u_{e,s_1} + \sum_{m,p,a} Y_{m,p,e,a} + \sum_{m,p,n} Y_{m,p,e,n} = t_e \cdot \sum_{s} u_{e,s} \qquad \forall e \qquad [16]$$

$$\sum_{m,p,a} Y_{m,p,e,a} - I_e \cdot \sum_{m,p,a} v_{m,p,e,a,s_0} \le 0 \qquad \forall e \qquad [17]$$

$$-\sum_{m,p,n} Y_{m,p,e,n} + I_e \cdot \sum_{m,p,n} v_{m,p,e,n,s_0} \le 0 \qquad \forall e \qquad [18]$$

The first allocation model computes the additional conservation areas necessary to reach a certain ecoregion target with one of two alternative distribution objectives. The first distribution objective minimizes representation differences across individual ecosystems and protects all ecosystems as equally as possible. The second distribution objective minimizes differences between the national contributions of EU member states to the protected area network. In the following, we describe the algorithm for the first distribution objective ('ecosystem equity' scenario) which involves equations [1]-[9]. The algorithm works similarly for the second distribution objective ('member state equity' scenario). We use the solution values of allocation model 1 as restrictions in allocation model 2. Our analysis also includes a 'cost-only' scenario, where we only solve allocation model 2. Both allocation models contain binary variables, and we solve them as a mixed integer program with GAMS/CPLEX version 24.8.3.

The technical realization of the first allocation model involves a sequence of model solutions over the index i. The objective variable L is maximized (equation [1]) but cannot exceed the lowest representation (R) of all included natural and semi-natural ecosystems (equation [2]). In all repetitions, we enforce the achievement of the ecoregion target (equation [3]). The first model execution ($i=i_1$) includes all ecosystems in the subset n_i. Equation [4] limits the expansion of the protected area to available areas of unprotected ecosystems. Equation [6] computes the representation levels of ecosystems, which may change from one iteration to the next. The initial optimization determines the highest general representation level of all individual ecosystems. We then identify all binding ecosystems (at least one), i.e., all ecosystems which have a non-zero marginal value in equation [2] or equation [4]. Non-zero marginal values in one of these equations indicate that these ecosystems cannot achieve higher representation levels. We remove these ecosystems from the subset n_i and save these ecosystems' solution values for the area selection variable (A*). In subsequent iterations, we force the selected area of all ecosystems excluded from subset n_i to remain at their saved levels (equation [9]) and maximize the lowest representation among all remaining ecosystems. This process continues until all ecosystems are removed from n_i. Equations [7] and [8] ensure that the model cannot select production land area to fill ecoregion representation gaps as long as there is still unprotected natural or seminatural ecosystem area left in an ecoregion. If all currently unprotected natural and seminatural ecosystem areas in an ecoregion are selected for protection (binary variable I=1) and an ecoregion is still underrepresented, the model closes the remaining gap by selecting additional area from production lands. Again, using equations [1], [2] and [6] and the iterative procedure described above, the model aligns protected area shares of production land types as equally as possible while at the same time fulfilling the ecoregion target (equation [3]). Equation [4] limits the expansion of protected area to currently unprotected areas of production land.

For the 'member state equity' scenario, the algorithm works similar to the 'ecosystem equity' scenario but aligns the protected area shares of all member states as equally as possible. Here again, the model cannot select production land area if there is sufficient unprotected natural or semi-natural ecosystem area available to fulfill a given ecoregion target. Once the model selected all natural and seminatural ecosystem areas, however, it fills remaining ecoregion gaps with production land. Equivalently to the above-described algorithm, the solution levels from allocation model 1 are then transferred to the second allocation model and form the right-hand-side values of equations [14] and [15].

The second allocation model determines the cost-minimizing expansion of protected areas within 504 planning units. For the 'cost-only' scenario, we solve the second allocation model in stand-alone mode including equations [11]-[13] and [16]-[18]. Equation [11] computes the total opportunity cost as the product of the additional selected ecosystem and production land area per planning unit times land cost of this planning unit summed over all planning units. Constraint [12] limits selectable ecosystem area to unprotected ecosystem area. Constraint [13] limits selectable production land area to unprotected production land area. Equation [16] enforces the achievement of the ecoregion target. Equations [17] and [18] ensure that the model cannot select production land area to fill ecoregion representation gaps as long as there is still unprotected natural ecosystem area left in an ecoregion.

For the ‘ecosystem equity’ and ‘member state equity’ scenarios, the additional constraints [14] and [15] enforce consistency between the solutions of the first and second allocation model. We deactivate the redundant equations [16]-[18] in these scenarios.

Supplementary

Table II.S1 *CORINE 2018 land cover data. We excluded the categories ‘1. Artificial surfaces’, ‘4.2.2 Salines’, and ‘5.2 - marine waters’ from our analysis. We used 29 land cover classes, which we divided into the two broad classes semi- or natural ecosystems and production land. We divided semi- or natural ecosystems further into seminatural grassland, seminatural forest, and other semi- or natural ecosystems and we divided production land into arable land, productive grassland, and production forest. All protection level values are rounded.*

CORINE land cover type	Broad land use class	Current protection level in Natura 2000 sites (%)	Current protection level in nationally designated PA (%)	Current total protection level (%)
2.1.1 Non-irrigated arable land	Arable land	7	7	14
2.1.2 Permanently irrigated land	Arable land	9	3	11
2.1.3 Rice fields	Arable land	22	2	25
2.2.1 Vineyards	Arable land	7	4	11
2.2.2 Fruit trees and berry plantations	Arable land	8	5	12
2.2.3 Olive groves	Arable land	8	1	10
2.3.1 Pastures, meadows and other permanent grasslands under agricultural use	Productive grassland	13	13	26
2.4.1 Annual crops associated with permanent crops	Arable land	10	3	13
2.4.2 Complex cultivation patterns	Arable land	7	7	14
2.4.3 Land principally occupied by agriculture, with significant areas of natural vegetation	Arable land	14	7	21
2.4.4 Agro-forestry areas	Arable land	26	1	27
3.1.1 Broad-leaved forest	Seminatural forest	35	9	44

3.1.1 Broad-leaved forest	Production forest	17	14	30
3.1.2 Coniferous forest	Seminatural forest	21	9	30
3.1.2 Coniferous forest	Production forest	9	11	20
3.1.3 Mixed forest	Seminatural forest	22	10	32
3.1.3 Mixed forest	Production forest	9	10	19
3.2.1 Natural grassland	Seminatural grassland	40	11	51
3.2.2 Moors and heathland	Other semi-natural ecosystems	46	9	55
3.2.3 Sclerophyllous vegetation	Other semi-natural ecosystems	36	4	40
3.2.4 Transitional woodland/shrub	Other semi-natural ecosystems	21	5	27
3.3.1 Beaches, dunes, and sand plains	Other semi-natural ecosystems	56	5	61
3.3.2 Bare rock	Other semi-natural ecosystems	62	8	69
3.3.3 Sparsely vegetated areas	Other semi-natural ecosystems	50	8	58
3.3.4 Burnt areas	Other semi-natural ecosystems	26	6	32
3.3.5 Glaciers and perpetual snow	Other semi-natural ecosystems	66	7	74
4.1.1 Inland marshes	Other semi-natural ecosystems	73	5	78
4.1.2 Peatbogs	Other semi-natural ecosystems	34	7	41
4.2.1 Coastal salt marshes	Other semi-natural ecosystems	90	4	94

4.2.3 Intertidal flats	Other semi-natural ecosystems	70	14	84
5.1.1 Water courses	Other semi-natural ecosystems	52	6	58
5.1.2 Water bodies	Other semi-natural ecosystems	32	6	37

Table II.S2 *Land rent data. Arithmetic mean of land rents in the period from 2009 to 2015 per NUTS-2 region in €/ha. Based on annual data provided by the FADN. We excluded some NUTS-2 regions (mostly big cities) from the network expansion due to data deficiencies (see N/A entries).*

NUTS-2 region	Arithmetic mean of land rent 2009-2015 (€/ha)	Comment
BE10	N/A	Brussels
BE21	261	
BE22	299	
BE23	322	
BE24	262	
BE25	396	
BE31	246	
BE32	278	
BE33	240	
BE34	130	
BE35	152	
BG31	127	
BG32	180	
BG33	253	
BG34	103	
BG41	64	
BG42	91	
CY00	168	
CZ01	N/A	Prague
CZ02	74	
CZ03	53	
CZ04	72	
CZ05	54	
CZ06	64	

CZ07	75	
CZ08	61	
DK01	435	
DK02	578	
DK03	551	
DK04	532	
DK05	557	
DE11	270	
DE12	139	
DE13	143	
DE14	217	
DE21	320	
DE22	372	
DE23	231	
DE24	155	
DE25	249	
DE26	236	
DE27	310	
DE30	N/A	Berlin
DE41	124	
DE42	209	
DE50	N/A	Bremen
DE60	694	
DE71	195	
DE72	132	
DE73	157	
DE80	219	
DE91	334	
DE92	408	
DE93	318	
DE94	505	
DEA1	499	
DEA2	373	
DEA3	482	
DEA4	315	
DEA5	243	
DEB1	142	

DEB2	185
DEB3	261
DEC0	89
DED1	142
DED2	140
DED3	202
DEE0	230
DEF0	331
DEG0	179
GR11	226
GR12	244
GR13	147
GR14	317
GR21	182
EL22	139
GR23	237
GR24	218
GR25	133
GR30	256
GR41	86
GR42	140
GR43	229
EE00	44
ES11	110
ES12	80
ES13	53
ES21	106
ES22	139
ES23	87
ES24	56
ES30	45
ES41	123
ES42	85
ES43	88
ES51	184
ES52	162
ES53	78

ES61	191	
ES62	343	
ES63	N/A	Ceuta (Morocco)
ES64	N/A	Melilla (Morocco)
ES70	1006	
FI13	158	
FI18	224	
FI19	209	
FI1A	162	
FI20	N/A	Aaland
FR10	173	
FR21	280	
FR22	207	
FR23	197	
FR24	140	
FR25	175	
FR26	179	
FR30	192	
FR41	132	
FR42	274	
FR43	123	
FR51	139	
FR52	145	
FR53	167	
FR61	223	
FR62	119	
FR63	93	
FR71	132	
FR72	118	
FR81	199	
FR82	208	
FR83	93	
FR91	308	
FR92	510	
FR93	N/A	Guyane
FR94	526	
HR03	66	

HR04	98
HU10	88
HU21	102
HU22	107
HU23	136
HU31	80
HU32	97
HU33	136
IE01	228
IE02	258
ITC1	180
ITC2	127
ITC3	318
ITC4	302
ITD1	510
ITD2	289
ITD3	375
ITD4	180
ITD5	317
ITE1	137
ITE2	177
ITE3	223
ITE4	182
ITF1	153
ITF2	85
ITF3	210
ITF4	176
ITF5	85
ITF6	157
ITG1	132
ITG2	63
LT00	63
LU00	175
LV00	29
MT00	95
NL11	535
NL12	652

NL13	587	
NL21	540	
NL22	668	
NL23	1229	
NL31	523	
NL32	1015	
NL33	799	
NL34	627	
NL41	767	
NL42	515	
AT11	202	
AT12	239	
AT13	N/A	Vienna
AT21	211	
AT22	282	
AT31	215	
AT32	171	
AT33	163	
AT34	123	
PL11	53	
PL12	62	
PL21	45	
PL22	45	
PL31	58	
PL32	39	
PL33	51	
PL34	68	
PL41	62	
PL42	63	
PL43	45	
PL51	67	
PL52	76	
PL61	81	
PL62	52	
PL63	94	
PT11	261	
PT15	258	

PT16	160	
PT17	267	
PT18	334	
PT20	149	
PT30	N/A	Madeira
RO11	69	
RO12	70	
RO21	73	
RO22	86	
RO31	89	
RO32	60	
RO41	82	
RO42	117	
SE11	N/A	Stockholm
SE12	177	
SE21	149	
SE22	345	
SE23	231	
SE31	64	
SE32	55	
SE33	74	
SI01	113	
SI02	110	
SK01	53	
SK02	67	
SK03	28	
SK04	25	
UKC1	106	
UKC2	104	
UKD1	62	
UKD2	167	
UKD3	N/A	Manchester
UKD4	159	
UKD5	N/A	Merseyside
UKE1	264	
UKE2	126	
UKE3	N/A	South Yorkshire

UKE4	N/A	West Yorkshire
UKF1	138	
UKF2	183	
UKF3	245	
UKG1	212	
UKG2	201	
UKG3	N/A	West Midlands
UKH1	249	
UKH2	179	
UKH3	201	
UKI1	N/A	Inner London
UKI2	N/A	Outer London
UKJ1	168	
UKJ2	131	
UKJ3	151	
UKJ4	139	
UKK1	141	
UKK2	163	
UKK3	174	
UKK4	116	
UKL1	96	
UKL2	154	
UKM2	111	
UKM3	61	
UKM5	116	
UKM6	15	
UKN	197	

Table II.S3 *Current protected shares of member states in the PA network and suggested protected shares under the three different Natura 2000 enlargement scenarios.*

Member state	**Current protected share (%)**	**Protected shares 30% ecoregion target (%)**			**Protected shares 50% ecoregion target (%)**		
		cost-only	**ecosystem equity**	**member state equity**	**cost-only**	**ecosystem equity**	**member state equity**
Austria	28	28	30	31	48	48	51
Belgium	25	29	30	29	37	37	44
Bulgaria	40	41	41	40	54	52	51
Croatia	37	38	42	41	56	65	53
Cyprus	54	54	54	54	54	54	54
Czech Republic	22	23	23	23	60	48	50
Denmark	15	18	18	24	24	24	50
Estonia	19	64	32	30	64	57	57
Finland	15	15	20	31	29	30	50
France	26	31	32	31	54	54	51
Germany	38	39	39	39	48	50	49
Greece	35	35	35	35	51	52	52
Hungary	23	24	28	24	37	41	50
Ireland	14	15	23	22	24	28	53
Italy	21	31	30	31	46	47	48
Latvia	18	53	24	27	53	52	48
Lithuania	17	26	20	20	38	40	51
Luxem-bourg	51	51	51	51	63	64	63
Malta	28	28	28	28	33	35	41
Nether-lands	15	23	23	23	23	23	45
Poland	40	40	40	40	59	57	51
Portugal	22	29	31	32	45	53	50
Romania	23	28	25	28	42	45	50
Slovakia	38	49	45	38	81	52	50
Slovenia	54	54	61	54	70	75	66
Spain	28	32	32	32	52	49	50
Sweden	15	37	42	33	66	66	52
The United Kingdom	28	37	34	34	57	56	49

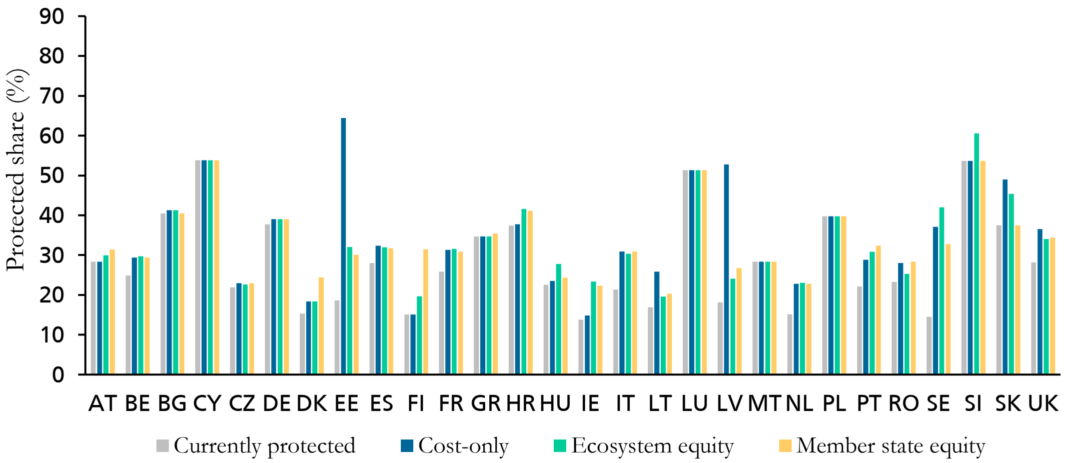

Figure II.S4.1 *Current protected shares of member states in the PA network and suggested protected shares under the three different Natura 2000 enlargement scenarios for the 30% ecoregion target.*

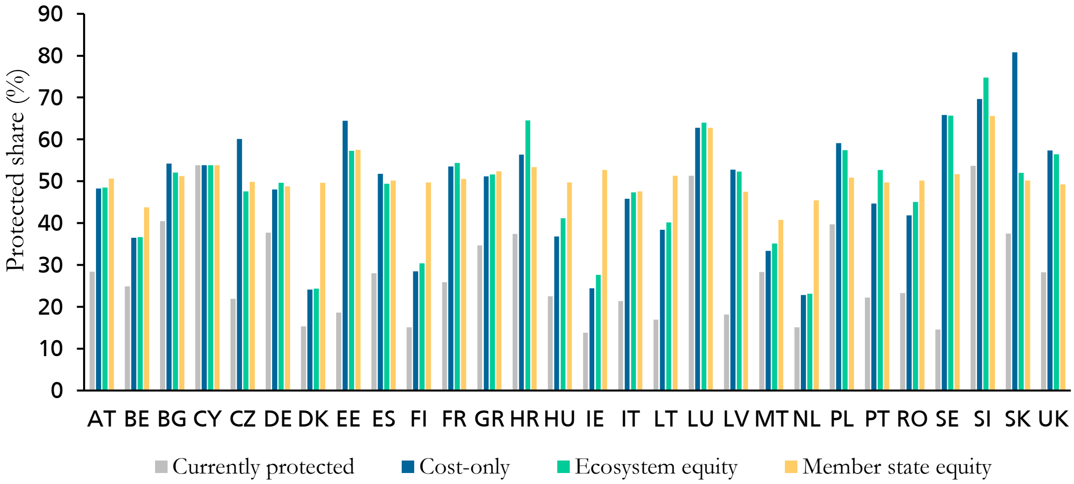

Figure II.S4.2 *Current protected shares of member states in the PA network and suggested protected shares under the three different Natura 2000 enlargement scenarios for the 50% ecoregion target*

Figure II.S5 Current protected area per land use class and modelled additional protected area needed for the 30% and 50% ecoregion representation target for the ten largest EU member states under the three different scenarios.

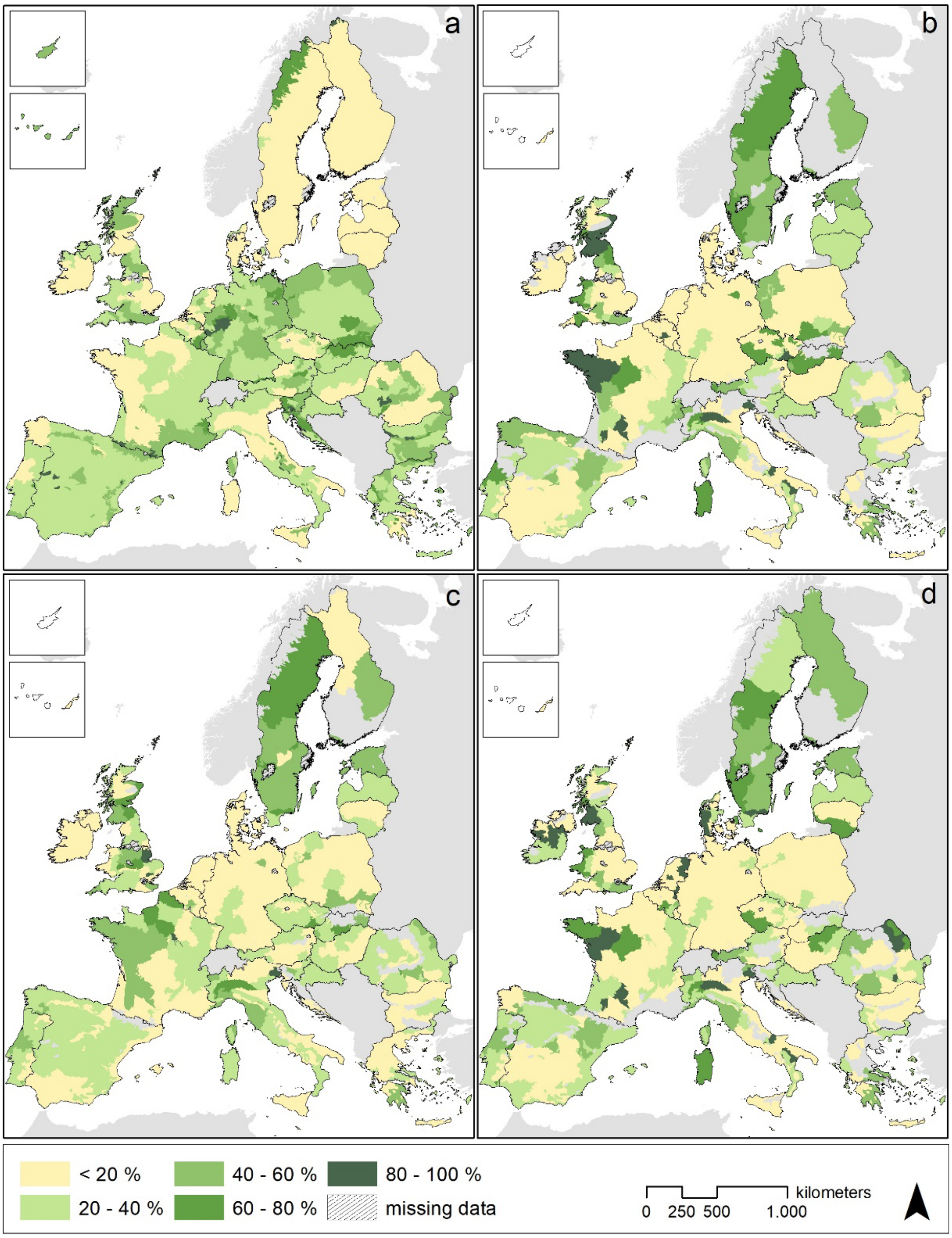

Figure II.S6 *Current protected shares of each planning unit (a, excluding CORINE artificial surfaces) and required shares of additional PAs for the 'cost-only' (b), 'ecosystem equity' (c) and 'member state equity' (d) scenario for the 50% ecoregion coverage target.*

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Versicherung an Eides statt

Declaration of oath

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation mit dem Titel: „Evaluating and systematically improving the European Union's nature protection network towards current and potential ecoregion representation targets" selbstständig verfasst und keine anderen als die angegebenen Hilfsmittel – insbesondere keine im Quellenverzeichnis nicht benannten Internet-Quellen – benutzt habe. Alle Stellen, die wörtlich oder sinngemäß aus Veröffentlichungen entnommen wurden, sind als solche kenntlich gemacht. Ich versichere weiterhin, dass ich die Dissertation oder Teile davon vorher weder im In- noch im Ausland in einem anderen Prüfungsverfahren eingereicht habe und die eingereichte schriftliche Fassung der auf dem elektronischen Speichermedium entspricht.

Hamburg, den 19. März 2020

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