SYNOPSIS

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Advances in conservation biogeography: towards protected area effectiveness under anthropogenic threats

Samuel Hoffmann[1]

[1] Department of Biogeography, University of Bayreuth, Universitaetsstr. 30, 95447 Bayreuth, Germany.
Email: samuel.hoffmann@uni-bayreuth.de

Abstract

This study endorses the main findings of a PhD thesis (Hoffmann 2020) and the manuscripts included intend to advance the success of protected areas in biodiversity conservation mediated through effective and efficient protected area management. The manuscripts provide missing scientific evaluations that modern conservation planning over large geographical extents requires: the comprehensive quantification of species diversity within and between protected areas; the development and application of efficient and effective in-situ monitoring and remote sensing of species diversity; and the assessment of anthropogenic climate change threats to protected areas. Moreover, the manuscripts aim at spreading conservation-minded data and knowledge by means of publishing open-access papers, open-source software and open data. This thesis synopsis is to stimulate a growing scientific and public debate on the effectiveness of protected areas and nature conservation under anthropogenic threats, which is necessary to stop nature's decline and thus guarantee a sustainable future for the welfare of generations to come.

Highlights

- Effective protected area management requires up-to-date information about states and trends of biodiversity and threats, and efficient tools to monitor them.
- Here I review the importance of protected area effectiveness for global biodiversity conservation, and how the manuscripts of my PhD thesis advance protected area effectiveness from the local to global scale.
- I particularly provide information about species diversity within and between protected areas of a continental estate, and about multiple dimensions of climate change threat to protected areas worldwide.
- I offer new insights and tools on how to monitor species diversity efficiently in the field and by remote sensing, and support the conservation movement by open-access publications, open-source software and open data.
- Perspectives are given on a global protected area management system and the next generation of conservation biogeographers.

Keywords: nature reserves, species diversity, ecosystem functioning, ecosystem services, climate change, monitoring, remote sensing

Motivation

We are currently in the midst of the sixth mass extinction event in earth history (Ceballos et al. 2015). This crisis is outstanding as the causes are not natural, such as asteroid collisions or volcanism, but the human species. About 1 million species are threatened with extinction at present and extinction rates are increasing (Díaz et al. 2019). The main drivers of this unprecedented biodiversity loss are human land use, exploitation of natural resources and organisms, anthropogenic climate change, environmental pollution and invasive species. The decline of nature is likely to continue in the near future because the driving forces result from powerful capitalistic systems and the consumptive needs of a growing human population striving after an increasing standard of living in a globalised world (Pereira et al. 2010, Díaz et al. 2019).

A dilemma evolves as human well-being depends on the protection of nature's integrity (Cardinale et al. 2012). We benefit from ecosystem functioning, goods and services, which build on biodiversity (Tilman et al. 2014). In addition, species have the right to exist independent of their benefits to humans (Wilson and Peter 1988). The use and existence values of nature are reasons for nature conservation and motivate me as a conservation biogeographer.

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I refer to conservation biogeography as 'the application of biogeographical principles, theories, and analyses, being those concerned with the distributional dynamics of taxa individually and collectively, to problems concerning the conservation of biodiversity' (Whittaker et al. 2005). Conservation biogeography combines the research disciplines of conservation biology and biogeography. Conservation biogeography has evolved from conservation biology but is deeply rooted in biogeography, which emerged as a distinct discipline as early as in the 19th century (Whittaker and Ladle 2011). Alexander von Humboldt was the first biogeographer who raised concerns about the human impacts on nature (von Humboldt 1845).

Conservation biogeography puts biodiversity into large spatial contexts. The mapping and modelling of species diversity of conservation concern over large geographical extents and over time lie at the core of conservation biogeography (Lomolino and Heaney 2004). The original agenda of conservation biogeography is to generate knowledge on how to optimise the conservation of biodiversity in space and time. Nowadays conservation biogeographers are facing manifold roles to stop the accelerating loss of biodiversity: they do not only generate the knowledge about biodiversity conservation in a geographical context but also implement, manage, monitor and adapt conservation initiatives in close cooperation and communication with stakeholders, such as policy-makers, managers, businesses, governmental and non-governmental organisations, local people and the general public.

Effective instruments for biodiversity conservation are protected areas (Watson et al. 2014). Protected areas are expected to be the only effective and efficient conservation tools in the future because a high degree of biodiversity will hardly be able to persist in the increasingly human-dominated landscapes of the Anthropocene (Watson et al. 2016). A proliferating number of conservationists propose setting aside half of terrestrial earth as protected areas, to compensate for the current loss of biodiversity and save our planet (Wilson 2016). The significance of protected areas for global biodiversity conservation is also reflected in the Aichi Biodiversity Targets, which is a set of 20 global targets under the Strategic Plan for Biodiversity 2011-2020, adopted by the signatories of the Convention on Biological Diversity (CBD) in 2010. Aichi Biodiversity Target 11 particularly focuses on protected areas stating that 'by 2020, at least 17% of terrestrial and inland water areas and 10% of coastal and marine areas, especially areas of particular importance for biodiversity and ecosystem services, are conserved through effectively and equitably managed, ecologically representative and well-connected systems of protected areas.' Therefore, the effectiveness of protected areas should not only be measured by protected area coverage but also by connectivity, management success and the diversity of nature conserved.

Given the importance of protected areas to stop biodiversity loss, protected areas were taken as the central theme of this PhD thesis synopsis. Within this synopsis, a protected area is defined as a geographical space that is dedicated to conserve biotic and abiotic features that represent values of nature for people. I particularly focus on biodiversity conservation from the species to the biome level via terrestrial protected areas, which is increasingly challenged by human land use and anthropogenic climate change.

Successful biodiversity conservation through protected areas requires effective and efficient management of protected areas as emphasised in Aichi Biodiversity Target 11. The extent of protected area is not necessarily an indicator for effective and efficient conservation (Geldmann et al. 2019, Barnes et al. 2018, Visconti et al. 2019), because the global protected area coverage is growing, while biodiversity is increasingly lost (Watson et al. 2014). This discrepancy triggered the development of other measurements for protected area management effectiveness, which is the ratio between the actual management result and the conservation target, and management efficiency, which is the ratio between the management results and efforts to reach the results. Measurements to quantify management effectiveness and efficiency are manifold due to the diversity of protected area designations, their management and conservation targets (Leverington et al. 2010). For example, the IUCN World Commission for Protected Areas established a renowned approach in which management evaluation includes the definition of assessable conservation goals, the estimation of applied resources, the selection of target indicators, the measurement of those indicators, and the analysis, interpretation and communication of results (Hockings et al. 2006). Furthermore, the Global Database on Protected Area Management Effectiveness (GD-PAME) was established (Coad et al. 2015) and the management effectiveness tracking tool (METT) records the quality of protected area management over time (Mascia et al. 2014). Such tools and databases are beneficial to assess the effects of protected area management on biodiversity conservation inside protected areas (Geldmann et al. 2018). The PAME metrics are, however, criticised for insufficiently considering biodiversity outcomes (Visconti et al. 2019).

The manuscripts here assessed provide missing scientific evaluations that are advantageous to effective and efficient conservation planning over large geographical extents: the comprehensive quantification of species diversity within and between protected areas; the development and application of efficient and effective in-situ monitoring and remote sensing of species diversity; and the assessment of anthropogenic climate change threats to protected areas. Moreover, the manuscripts aim at spreading conservation-minded data and knowledge by means of publishing open-access papers, open-source software and open data. Consequently, this thesis intends to advance the success of protected areas in biodiversity conservation. It is to stimulate a growing scientific and public debate on the effectiveness of protected areas and nature conservation under anthropogenic threats, which is necessary to stop nature's decline and thus guarantee a sustainable future for the welfare of generations to come.

Synthesis

In conservation biogeography, the multiple roles of protected areas are studied, which aim at preserving values and objectives of nature (Ladle and Whittaker 2011a). The success that protected areas had during the 21st century (Watson et al. 2014, Bingham et al. 2019, Lewis et al. 2019) is threatened, primarily by human land use (Schulze et al. 2018) and climate change (Hannah 2008, Peters and Darling 1985, Gross et al. 2017, Thomas and Gillingham 2015, Araújo et al. 2011). Threats to biodiversity are occurring globally (Díaz et al. 2019) and biodiversity is rapidly lost (Pimm et al. 2014). Consequently, protected area planning and management has not only to become more effective and efficient, but also needs to consider local to global scales to ensure biodiversity conservation worldwide. In the following, I explain how each manuscript can advance effectiveness and efficiency of protected areas in preserving biodiversity at the local to global extent (Table 1).

Quantifying species diversity within and between protected areas of a continental estate

The scientific prerequisites of successful management are the research and monitoring of management effectiveness, i.e. the degree to which conservation targets are met by protected area management (Hockings et al. 2006). Species diversity is a reasonable indicator of protected area management effectiveness (Le Saout et al. 2013). However, species diversity is not entirely known inside many protected areas, because management resources are limited and thereby only priority species are considered in conservation measures. In Hoffmann et al. (2018), we accordingly analysed the current distributions of priority species within major protected areas in the EU. The study includes 1303 species in ten taxa. These priority species are listed in the annexes of the Birds and Habitats directives, the two most important policies for species conservation in the EU. Member states are obliged to periodically report the occurrence of those focal species. We used these occurrence data and merged them with 285 national parks and 147 UNESCO Man and Biosphere (MAB) reserves, which are two major protected area

Table 1. Overview of the manuscripts included in this thesis and how they advance the scientific foundation of effective and efficient protected area management.

Scientific advances in management	Be informed about multiple measures of species diversity within protected areas to increase management effectiveness from the local to continental extent	Have knowledge of monitoring beta diversity efficiently using remote sensing	Be aware of how to increase the efficiency of biodiversity surveys under limited management resources
Openness	Open access, open data	Open access, open data, open source code	Open access, open data
Grain	10 km, individual protected areas	10 m	2 m
Extent	EU	Elevation gradient of 2,400 m	Nine 400 m²-plots
Methods	Geospatial analyses, species-area relationships, sensitivity analyses	Univariate and multivariate statistics, time series and sensitivity analyses	Modelling information entropy
Data sources	Eionet, WDPA, Le Saout et al. (2013)	In-situ survey, Copernicus, Spanish National Geographic Institute, Irl et al. (2015)	In-situ survey
Conservation threats	Not specified	Invasive species, human land use	Climate change
Conservation objectives	Diversity of the priority species listed in the EU Birds and Habitats directives	Perennial plant species diversity and communities	Plant species diversity of alpine grassland
Protected areas	National parks, UNESCO MAB reserves	La Palma UNESCO MAB Reserve	Gran Paradiso National Park
Manuscript	Hoffmann et al. (2018)	Hoffmann et al. (2019b)	Hoffmann et al. (2019c)

Table 1. Continued...

Scientific advances in management	Acquire open data on threatened species diversity	Be informed about the potential climate change impacts on protected areas to sustain management effectiveness from the local to global extent	Be informed about the potential climate change impacts on protected areas to sustain management effectiveness from the local to global extent
Openness	Open access, open data	Open access, open data	Open access, open data
Grain	2 m	ca. 1 km, individual protected areas	ca. 1 km, individual protected areas
Extent	Nine 400 m^2-plots	Global	Global
Methods	In-situ survey	Temporal modelling, geospatial and sensitivity analyses	Temporal modelling, geospatial and sensitivity analyses
Data sources	In-situ survey	WDPA, WorldClim, Amatulli et al. (2018), Le Saout et al. (2013), Olson et al. (2001), Venter et al. (2016)	WDPA, WorldClim, Amatulli et al. (2018), Le Saout et al. (2013), Olson et al. (2001), Venter et al. (2016)
Conservation threats	Climate change, land use change	Climate change, human land use, invasive species	Climate change, human land use, invasive species
Conservation objectives	Plant species diversity of alpine grassland	Biodiversity with focus on biomes and IUCN Red List species	Biodiversity with focus on countries, IUCN Red List species and ecosystem services
Protected areas	Gran Paradiso National Park	Terrestrial protected areas worldwide	Terrestrial protected areas worldwide
Manuscript	Hoffmann et al. (2019**d)**	Hoffmann et al. (2019**a)**	Hoffmann and Beierkuhnlein (2020)

designations focusing on species conservation. We then applied a novel, multifunctional approach to calculate different metrics of conservation value that represent different components of species diversity, involving inventory diversity, deviation from the species–area relationship, species rarity and differentiation diversity. We offer this approach to evaluate how much biodiversity is found inside protected areas (i.e. protected areas' representativeness), which can be used to enhance protected area management effectiveness, e.g. by trying to preserve more or more diverse species. We show that individual protected areas significantly vary in their species diversity, which is often not associated with protected area size (Fig. 1). Protected areas at the margins of EU territory harbour only few species but are key to conserving rare species. This analysis allows a multi-facetted and more accurate estimation of the conservation value of European protected areas than global-extent approaches. While similar studies consider only single species diversity indices, Hoffmann et al. (2018) accounts for a multitude of species diversity metrics. It shows that more comprehensive conservation strategies can be delivered if inventory, differentiation and proportional diversity are integrated. This study highlights the present conservation value of renowned European protected areas in terms of species diversity. It informs protected area management from a local to continental perspective.

Using remote sensing for efficient monitoring of species diversity

In the face of the high rates of current biodiversity loss (Díaz et al. 2019, Ceballos et al. 2015, Barnosky et al. 2011, Pimm et al. 2014), the monitoring of the biotic and abiotic environment needs to become time and cost-efficient. Remote sensing is a growing, time- and cost-efficient tool for conservation (Horning et al. 2010, Turner et al. 2015, Rocchini et al. 2019). In the biodiversity conservation context, remote sensing techniques have been primarily used to estimate plant species richness and abundance (i.e. alpha diversity), whereas the assessment of differentiation diversity (i.e. beta diversity) has been neglected, even though beta diversity is crucial for conservation planning (Socolar et al. 2016). Therefore, one article of the synopsis contributed to the analysis of beta diversity using remote sensing techniques. In Hoffmann et al. (2019b), we investigated the capability of remote

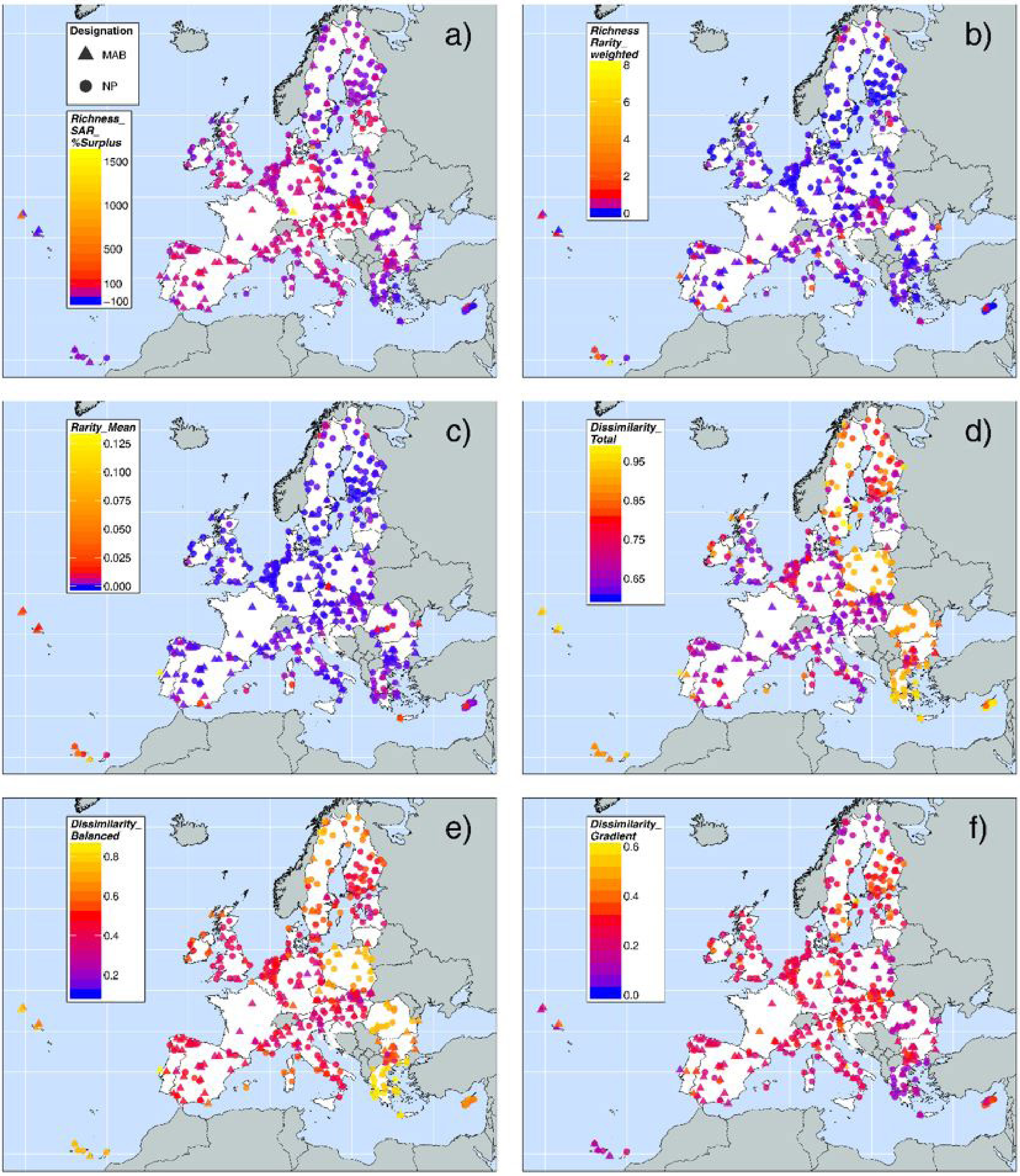

Figure 1. Metrics of conservation value for national parks (NP) and UNESCO Man and Biosphere Reserves (MAB) in the European Union. a) Area-controlled surplus of reported species (Richness_SAR_%Surplus) accounts for the effect of area on reported species richness. It reveals the percentage deviation between observed Richness_RS and predicted Richness_RS, as modelled by the species–area relationship considering observed reported species richness and protected area. b) Rarity-weighted richness (Richness_Rarity_weighted) integrates reported species richness and rarity. It is a measure of the protected area's reported species richness, but weighted by the conservation weights of reported species. c) Average rarity (Rarity_Mean) is calculated by Richness_Rarity_weighted over Richness_RS. It represents the average rarity of reported species within the protected area. d) Total dissimilarity (Dissimilarity_Total) indicates beta diversity between protected areas regarding their species composition. e) Balanced dissimilarity (Dissimilarity_Balanced) and f) gradient dissimilarity (Dissimilarity_Gradient) are the additive components of total dissimilarity (Baselga 2013). For details see Hoffmann et al. (2018).

sensing signals to reflect plant communities in the La Palma UNESCO MAB Reserve. If open remote sensing data are able to accurately account for the dissimilarity between species assemblages, this would allow time and cost-efficient monitoring of differentiation diversity. We calculated structural remote sensing variables from airborne LiDAR data and a time series of multispectral Sentinel-2 (S2) images. Additionally, we surveyed perennial vascular plant species abundances in three pre-defined community types: succulent scrubland, *Pinus canariensis* forest and subalpine scrubland. We show that up to 85% of beta diversity is reflected by the remote sensing variables in the wet season (Fig. 2). The LiDAR variables explain less variation of beta diversity than the S2 variables. The explanatory power of S2 variables decreases with increasing grain size, while the explanatory power of LiDAR variables increases. Accordingly, we demonstrate that open remote sensing data are able to accurately reflect plant communities. Such remote sensing approaches, however, need to be complemented by field surveys to reveal the complete variation in community composition.

Optimising field surveys for efficient monitoring of species diversity

In contrast to remote sensing, in-situ surveys are classic approaches to assess species diversity inside protected areas. In-situ sampling procedures can, however, still be improved (Rada et al. 2019, Serra-Diaz and Franklin 2019). This leads to Hoffmann et al. (2019c), where we developed a time and cost-efficient sampling design for field surveys. The ongoing mass extinction of species does not allow for inefficient surveys that require a lot of staff, time and funds. Surveys and monitoring schemes need to be optimised, that means the ratio between the amount of information collected and sampling effort has to be maximised (Vicente et al. 2016). Hoffmann et al. (2019c) concentrates on endangered alpine grassland in Gran Paradiso National Park, Italy, but the approach we developed can be adapted to any other ecosystem. The methodological code is attached to this open-access publication. The sampling effort in grassland increases with the number and size of sampling units. To optimise sampling effort, we were searching for the size and number of sampling units (i.e. plots) that provide the maximal amount of information with minimal effort. Nine 20 m × 20 m-plots were surveyed, each consisting of 100 2 m × 2 m-subplots. Species richness and Shannon diversity (Shannon 1948) were calculated for different sizes and quantities of subplots. We simulated larger subplot sizes by unifying adjacent 2 m × 2 m-subplots. Shannon's information entropy was then applied to measure the information content among richness and diversity values resulting from different subplot sizes and quantities. The optimal size and number of subplots is the lowest size and number of subplots returning maximal information. We found that the information content among richness values increases with subplot size which is not related to the number of subplots (Fig. 3). Subsequently, the largest subplot size available is the optimal size for information about richness. We also show that information content among diversity values increases with subplot size when 18 or less subplots have been considered, and decreases when at least 27 subplots have been surveyed. Therefore, the subplot quantity determines whether the smallest or largest subplot size available is the optimal size, and whether the optimal size can be generalised across

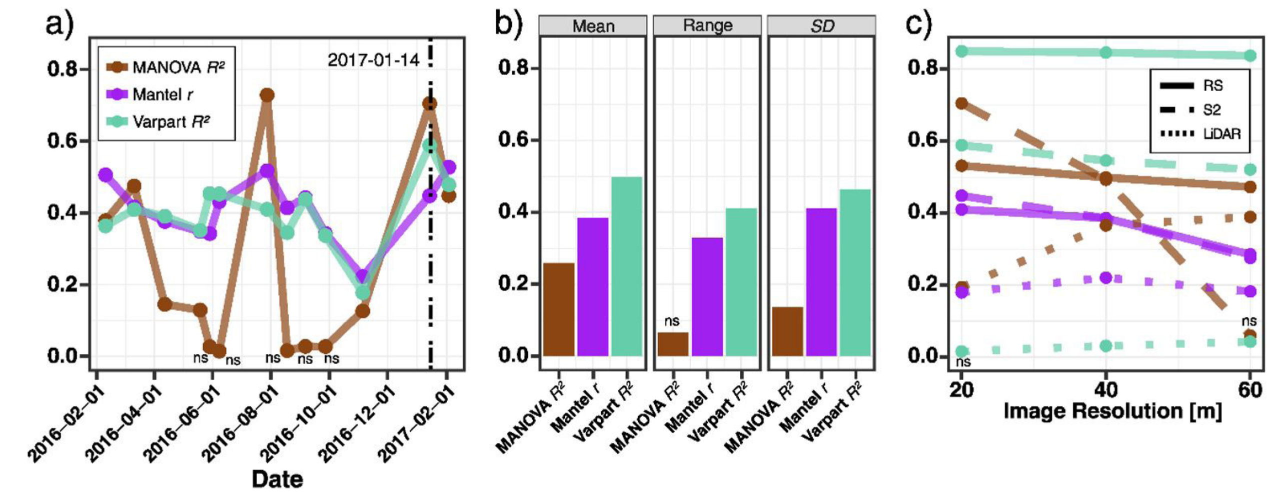

Figure 2. Time series analysis of Sentinel-2 (S2) images and sensitivity analysis concerning grain size. In a) the date-specific correlation results between the S2 variables of 13 images (20-m grain size) and the β-diversity of plant communities are shown. Part b) shows the correlation results applying the multitemporal mean, range (|max-min|) and SD of the time series of S2 variables. The S2 image from 14 Jan 2017 indicates the strongest correlation from the three statistical tests (MANOVA, Mantel test, variation partitioning). This S2 image was used for the sensitivity analysis in c). Here, we show the statistical results for coarser grain sizes (40 and 60 m) by aggregating the RS-derived metrics (i.e. taking the mean value). "Ns" highlights non-significant ($p \geq 0.05$) correlation results. For details see Hoffmann et al. (2019b).

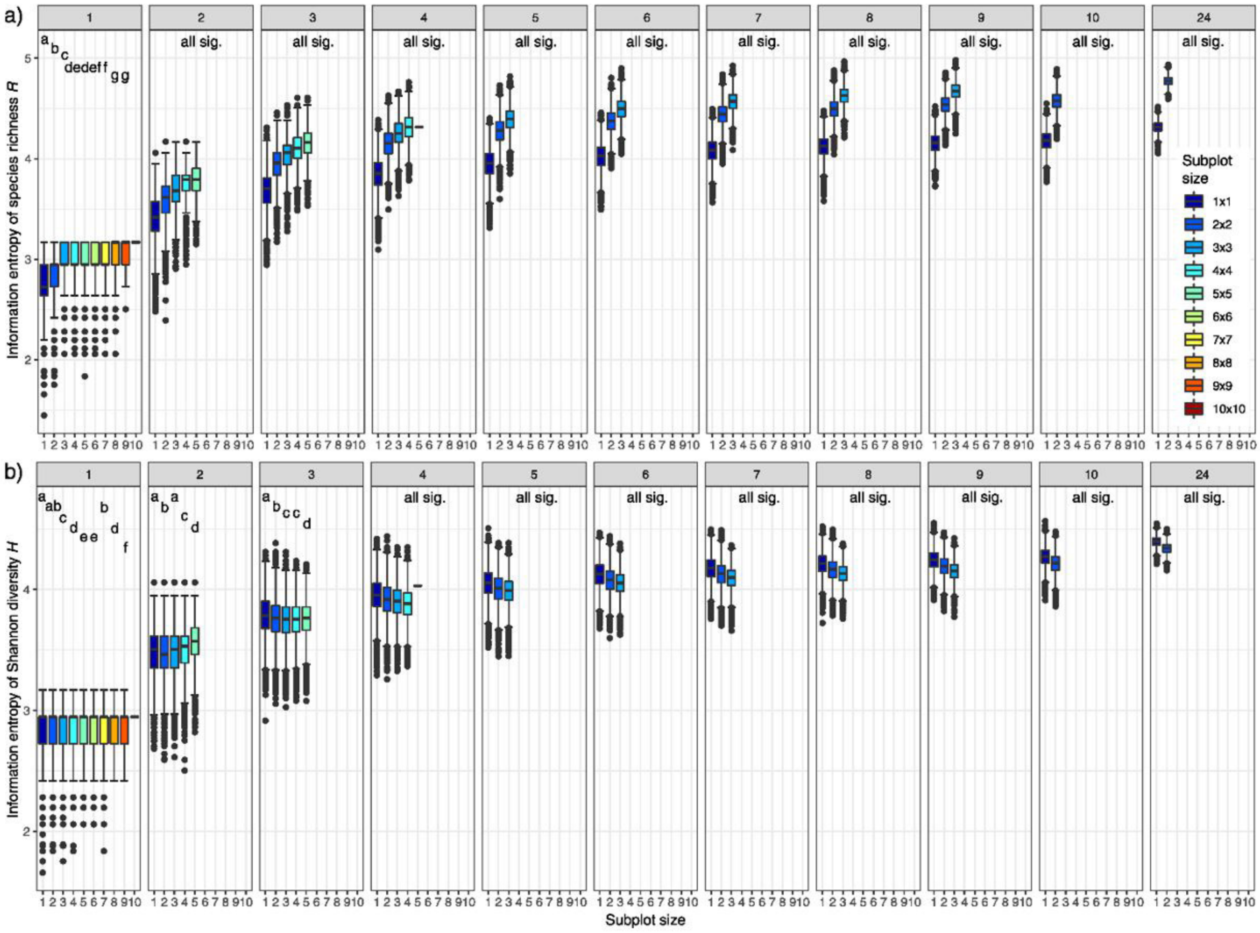

Figure 3. Information entropy versus plot size given a constant number of plots. In a) Shannon's information entropy of species richness R was separately calculated for different quantities of subplots m (number inside grey boxes) that were randomly selected from each of the nine 10 × 10-plots. This random selection procedure was repeated 10,000 times, so that 10,000 entropy values were calculated per subplot size for a given constant number of subplots (see Hoffmann et al. (2019c) for details). In b) Shannon's information entropy of the Shannon diversity H was calculated. 3. The letters above boxplots illustrate significant differences ($p < 0.05$) between entropy distributions using Mood's median test. "All sig." indicates that all entropy distributions are significantly different from each other. For the subplot size 1 × 1 and m = 100 and for 5 × 5 and m = 4, repetitions of the random selection procedure were not reasonable because these configurations already incorporated all independent subplot-unions available within a 10 × 10-plot by one single selection run. They were excluded from Mood's median test. For details see Hoffmann et al. (2019c).

both, species richness and diversity. Given a 2 m × 2 m size, we estimated an optimal quantity of 54. Given a size of 4 m × 4 m, we estimated an optimal number of 36. The optimal number of plots can be generalised across both indices because it barely differed between the indices given a fixed subplot size. Effective and efficient in-situ sampling designs can be created with this approach.

Opening data, software and literature to advance biodiversity conservation

In Hoffmann et al. (2019d), we thoroughly describe and provide open data on the alpine grassland diversity, which was studied in Hoffmann et al. (2019c). Hoffmann et al. (2019d) is to share data on this threatened vegetation type, which will support research and conservation of this ecosystem in the future. Open-access literature, open-source software and open data are generally beneficial to timely conservation assessments. Hence, each manuscript of the thesis is open-access and code produced in the manuscripts is open as well, to ensure the spread of knowledge and to advance biodiversity conservation.

Assessing anthropogenic climate change threats to the global protected area estate

Threats to biodiversity must be identified inside protected areas in order to stop the loss of biodiversity from protected areas. Climate change is a major threat to biodiversity conservation (Ripple et al. 2019, Hannah 2008), which acts on the local extent of protected areas worldwide. While protection status may prevent human-induced land use change and habitat degradation, the influence of anthropogenic climate change on protected areas cannot be stopped by protected area management. Previous literature accounting for climate change impacts on protected areas is biased towards small geographical extent or large grain size. The literature considers a limited geographical extent only, such as China (Zomer et al. 2015), Brazil (Lapola et al. 2019), Amazonia (Feeley and Silman 2016), the tropics (Tabor et al. 2018), North America (Batllori et al. 2017, Carroll et al. 2017, Gonzalez et al. 2018) or Europe (Nila et al. 2019, Barredo et al. 2016, Araújo et al. 2011). A spatially high-resolution assessment of local climate change impacts inside protected areas worldwide is required to guide local protected area management towards global conservation goals (Felton et al. 2009). Loarie and colleagues provide such an assessment, but that is restricted to temperature change (Loarie et al. 2009). A global assessment of the local climate change impacts on protected areas is missing but essential to guide local protected area management towards global conservation goals. Hoffmann et al. (2019a) and Hoffmann and Beierkuhnlein (2020) address this knowledge gap. In both manuscripts, we analysed several facets of climate change onto terrestrial protected areas worldwide by the year 2070 applying a moderate and severe emission scenario.

Hoffmann et al. (2019a) is about predicted climate shifts within protected areas, using a fine spatial grain of approximately 1 km. We incorporated 137,432 individual protected areas, i.e. 99.9% of the world's terrestrial protected areas. If species are forced to migrate from protected to unprotected areas to track suitable climate conditions that disappeared from the protected area, they may face degraded habitats in anthropogenic landscapes. Extinction threat consequently increases and protected areas lose biodiversity and associated values they were meant to provide (Hannah et al. 2007, Araújo et al. 2004, Velazco et al. 2019, Bagchi et al. 2013, Barredo et al. 2016, Holsinger et al. 2019, Langdon and Lawler 2015, Regos et al. 2016). Species loss within protected areas is rarely compensated for by incoming taxa (Burns et al. 2003, Coetzee et al. 2009, Araújo et al. 2011, Fuentes-Castillo et al. 2019). We found that protected areas in the temperate and northern high-latitude biomes experience especially high proportions of climate conditions that are predicted to be novel within the protected area network in a local, regional and global context by the year 2070 (Fig. 4). By relating characteristics of protected area design to the predicted climate shifts, we could estimate the future impacts of anthropogenic climate change on the performance of protected areas in biodiversity conservation. Small protected areas of temperate biomes in lowland regions with low environmental heterogeneity and high human pressure but low irreplaceability for threatened species will lose especially high proportions of their currently protected climates. This analysis directs adaptation measures towards protected areas that are strongly affected by climate change, of low adaptation capacity and of high conservation value.

Hoffmann and Beierkuhnlein (2020) complements Hoffmann et al. (2019a) by quantifying local climate change exposure of the world's terrestrial protected areas, applying the same resolution as in Hoffmann et al. (2019a), i.e. ca. 1 km. In Hoffmann and Beierkuhnlein (2020), climate change was calculated by climate anomaly, i.e. the magnitude of climate change (Garcia et al. 2014). Here we show that local climate anomalies in the year 2070 are predicted to be highest inside protected areas of the (sub-)tropical and polar countries (Fig. 5). Moreover, we found that, globally, protected areas showing large climate anomalies tend to be at high elevation and highly irreplaceable for threatened species, indicating high climate change vulnerability. These protected areas are relatively large in area, of high environmental heterogeneity and less pressured by humans, reducing climate change vulnerability. Large areas, high environmental diversity and low human pressures generally favour nature conservation under climate change (Triantis and Bhagwat 2011, Ackerly et al. 2010, Lawler et al. 2015, Heller et al. 2015, Scherrer and Körner 2011, Comer et al. 2015, Irl et al. 2015, Thomas and Gillingham 2015). This study expands Hoffmann et al. (2019a) by analysing a different dimension of climate change and focusing on countries instead of biomes. It can support climate-smart protected area management and policy from the local to global extent, particularly addressing national authorities. Both manuscripts address the need to investigate multiple dimensions of threat to the effectiveness of the global protected area estate (Bonebrake et al. 2019). Both manuscripts reveal different aspects of the climate change impacts on protected areas, which promote climate-smart planning and management of local protected areas worldwide. However, individual recommendations for climate-wise management cannot be given here, because the ideal management application depends on the local context of protected areas. Accordingly, many theories, frameworks and guidelines for climate-smart conservation planning and management have been developed (e.g. Belote et al. 2018, Ando et al. 2018, Reside et al. 2018).

Future perspectives

Towards a global protected area management system

Protected areas offer solutions to the sixth mass extinction event in earth history and are preferred conservation policies given climate change (Hagerman and Satterfield 2014). Aichi Biodiversity Target 11 sets a terrestrial protected area coverage of 17% as a conservation target, but protected area extent does not indicate protected area effectiveness (Kati et al. 2015, Barr et al. 2011, Joppa and Pfaff 2009, Visconti et al. 2019, Rodrigues et al. 2004). For that reason, a certain degree of management effectiveness of the global protected area estate should become a legally binding global conservation target as well.

The aim of this study is to stimulate coordinated biodiversity conservation through protected areas at the national and international level, by providing information about biodiversity and threats within individual protected areas of continental to global

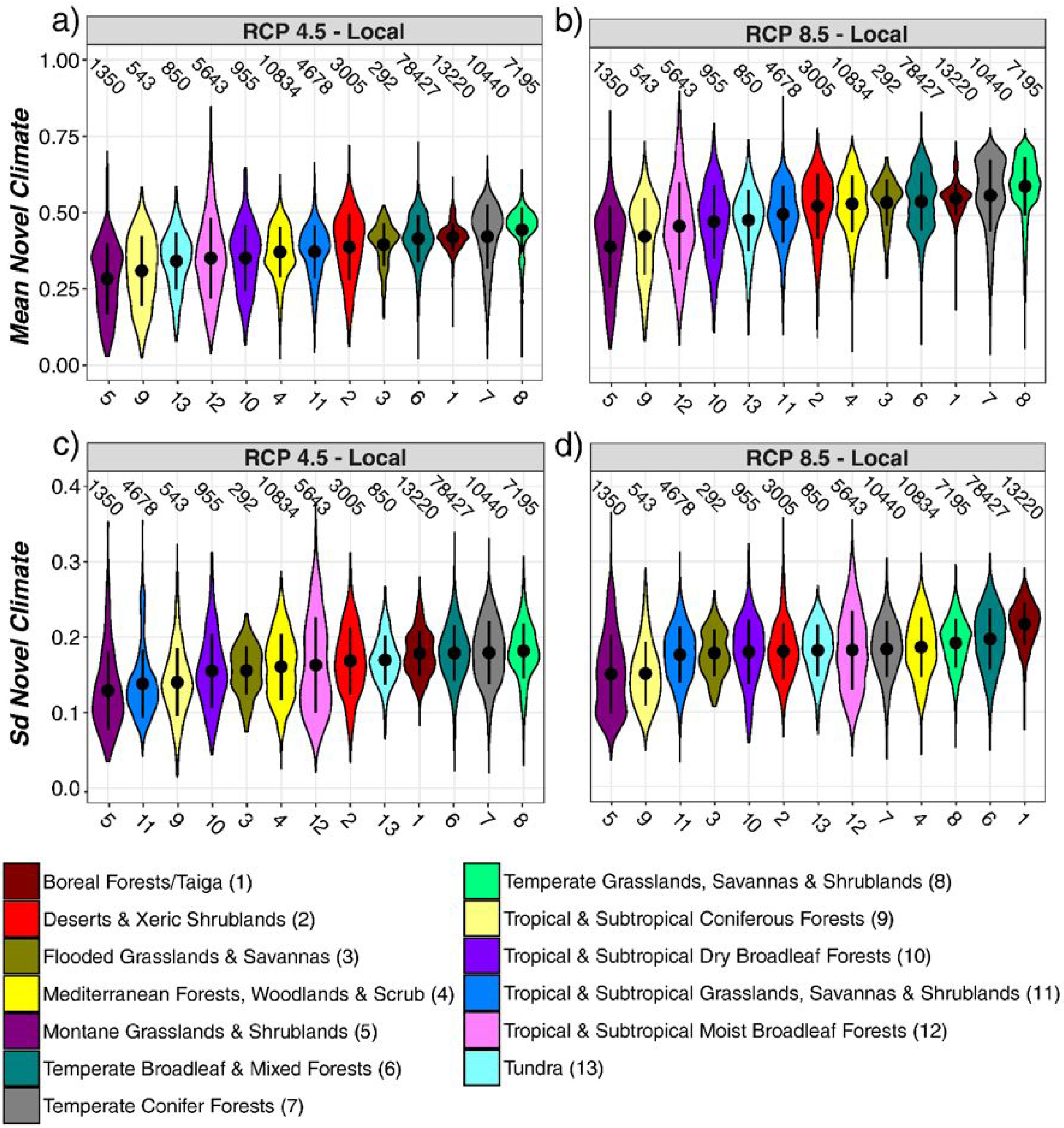

Figure 4. Local-scale novel climate index of terrestrial protected areas worldwide, summarized by biomes. The mean of the local-scale novel climate index under a) RCP 4.5 and b) RCP 8.5. The standard deviation (sd) of the local-scale novel climate index under c) RCP 4.5 and d) RCP 8.5. Sd represents the variation of the local-scale novel climate index resulting from ten GCMs. Violins per biome are ordered by increasing mean. Black dots and attached lines within violins represent the mean ± standard deviation. Black numbers above violins indicate the number of PAs within the respective biome. For details see Hoffmann et al. (2019a).

networks. Each manuscript of this thesis contributes to biodiversity conservation in a specific way. However, a comprehensive analysis that reveals the complex relationships between nature's various values, conservation objectives and threats inside the global protected area estate has not been realised yet. This is a main future, albeit ambitious, perspective in conservation biogeography. Such a comprehensive and global analysis should be conducted frequently to ensure the long-term preservation of nature by protected areas across the globe. It is consequently necessary to establish long-term monitoring of nature and threats within protected areas all over the world. Artificial intelligence and deep learning are promising

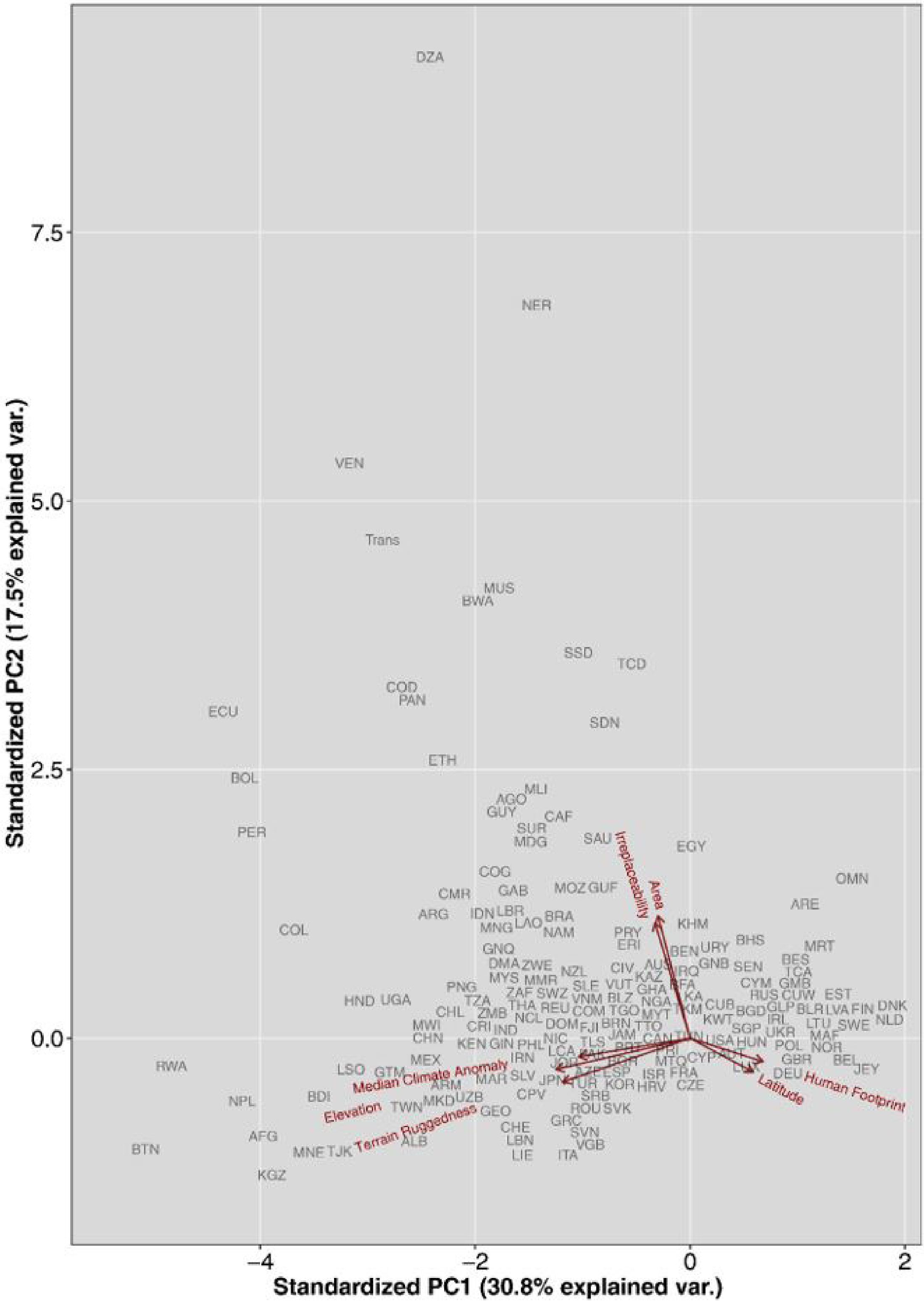

Figure 5. Principal components analysis of the PAs’ median climate anomalies (2070, RCP 8.5) and other PA characteristics grouped by countries. The PA characteristics ‘area’, ‘elevation’ and ‘terrain ruggedness’ indicate the PAs’ capacity to buffer the climate change impact; ‘irreplaceability’ represents the PAs’ importance for the conservation of globally threatened species. By relating the predicted climate anomalies to the PA characteristics at the country level, we provide additional information about the climate change vulnerability of national PA estates. PAs are assumed to be particularly vulnerable to climate change when the predicted climate anomalies, the human footprint and irreplaceability are high, while the area, elevation and terrain ruggedness are low. The alpha-3 country codes are given (i.e. ISO 3166). ‘Trans’ refers to transboundary PAs. For details see Hoffmann and Beierkuhnlein (2020).

computational technologies for nature conservation since they enable an automated classification of big monitoring data (Lamba et al. 2019). Nevertheless, resources for monitoring are limited. Given that, only a selection of variables can be prioritised. Scientists have recently argued for sets of essential variables that reflect states and trends of nature. These essential variables relate to climate (Bojinski et al. 2014), oceans (Constable et al. 2016), biodiversity (Pereira et al. 2013, Jetz et al. 2019), geodiversity (Schrodt et al. 2019) and progress towards Sustainable Development Goals (SDG) (Reyers et al. 2017). The definition of essential variables has led to advances in data collection, storage, distribution and use (Kissling et al. 2015) that are essential to big data analyses. Remote sensing (Pettorelli et al. 2016) and long-term ecological research stations (Haase et al. 2018) are sophisticated techniques to monitor essential variables.

Such big data analyses should form the basis of large-scale protected area management systems. There are many examples of management frameworks for conservation under rapid environmental changes (Westgate et al. 2013, Gillson et al. 2019, Rannow et al. 2014, Shoo et al. 2013). Gillson and colleagues (2019) developed an advanced adaptive management cycle providing appropriate tools and approaches for integrating multiple forms of evidence to understand and manage complex dynamic systems. Such adaptive management concepts help to model future dynamics of nature with respect to social, political and economic criteria and developments. Such frameworks could be applied to the global extent and local grain of protected areas to support local conservation action which is globally coordinated. This could be the basis for a globally coordinated protected area management system.

The World Database on Protected Area (WDPA) (IUCN and UNEP-WCMC 2019, Bingham et al. 2019) and the Digital Observatory for Protected Areas (DOPA) could be a role model for such a global protected area management system. The European Commission's Joint Research Centre (JRC 2019) developed DOPA as a web based information system on the world's protected areas. The DOPA monitors the state of and threats to protected areas by using global data sets. From these data indicators are derived that measure progress towards Aichi Biodiversity Target 11, and SDG 14 and 15. Therefore, the DOPA is already providing a scientific foundation for a globally coordinated management system for protected areas. I consider the development and application of such a global protected area management system as a crucial future task for conservation biogeographers, to reach the global biodiversity and sustainability goals.

Next generation conservation biogeography

Conservation biogeography is advancing the effectiveness of protected areas but faces many future challenges that are not related to protected areas. Filling biogeographical knowledge gaps and improving biodiversity forecasts are persistent scientific challenges. Turning theory into practice, educating, communicating and changing social values and lifestyles are common practical challenges. Accepting these challenges, conservation biogeographers need to focus on large geographical extents but small grain because threats to nature are occurring locally all over the world (Alagador 2020). Global conservation problems beyond 2020 can only be solved by local conservation strategies that are globally coordinated via international collaboration (Mace et al. 2018).

Conservation research is restricted by the unavailability of data. Growing conservation knowledge evolves from an increasing quality and quantity of data (Wüest et al. 2019). Conservation biogeographers work on the Linnean, Wallacean and extinction estimate shortfalls by collecting new data (Ladle and Whittaker 2011b). However, temporal and financial resources for collecting data and monitoring are limited. Hence, sampling and monitoring techniques need optimisation to become less time-consuming and costly. Open information systems, data repositories, databases and data sets play a central role to foster global conservation research by the coming generations of conservation biogeographers. Varying quality, bias, noise and uncertainty within data require meta-data in order to efficiently harvest and analyse the data (Wohner et al. 2019, Wüest et al. 2019). Open-source software advances data analyses, their documentation, transparency and reproduction. Furthermore, citizen science is a promising tool to enhance data collection, monitoring and analysis by participating citizens. Citizen science brings the scientific community and the public together, which supports public education and nature conservation at the same time (Devictor et al. 2010, Danielsen et al. 2014, Sullivan et al. 2014, McKinley et al. 2017). However, the increasing availability of data should not prevent anyone collecting new, high-quality data, especially in time of rapid environmental changes. More scientists need to be trained to enhance the quality and quantity of available data and methods in the future.

Predictions are to some degree uncertain and uncertainty may prevent decision-makers from acting (Gray 2011, Michalak et al. 2017, Bagchi et al. 2013, Wang et al. 2012, Midgley et al. 2007, Millar et al. 2007, Pacifici et al. 2015, Conroy et al. 2011, Hallegatte 2009, Belote et al. 2018). There are, nevertheless, approaches to decision-making in the conservation context that account for model uncertainties (Polasky et al. 2011, Hoekstra 2012, Hayes et al. 2013, Yousefpour and Hanewinkel 2016). A future challenge is to minimise the uncertainties of model predictions, e.g. by probabilistic analyses (Billionnet 2015, Alagador et al. 2016), considering past dynamics (Di Marco et al. 2015), using sensitivity analysis and null-models (Feeley and Silman 2010), and incorporating as many relevant hypotheses, data and models as possible (Michalak et al. 2017, Conroy et al. 2011). Forecasts are improved by refined theories as well as by the consideration of scale-dependency, inadequacies of input data and sensitivity of projections to model structure and parameterisation (Whittaker et al. 2005, Araújo and New 2007). However, in contrast to meteorologists, ecologists still miss a comprehensive theory to sufficiently predict complex ecosystem assemblies (Higgins 2017), which would promote the human ability to safeguard nature.

In the view of the current rates of nature's declines, another important task for conservation biogeographers is to work harder on improving the communication and collaboration between stakeholders, such as scientists, policy-makers, managers and people (Costello et al. 2015). Publishing open-access is a substantial first step to communicate research efficiently. Nature conservation is a value-laden field, which can complicate communication. Studies have shown that effective conservation policy and management is based on well communicated, explained and contextualised research (Kalliola et al. 2008, Manfredo et al. 2016, Morrison 2016). Therefore, researchers need to translate their findings into a plain language that stakeholders understand. If stakeholders recognise that their well-being depends on nature conservation, they may be willing to support conservation. Using social media is an efficient way of communicating science, though not without pitfalls (Bombaci et al. 2016). In contrast, academic media do not reach the majority of people (Knuth and Jacobson 2000) and traditional media tend to be prone to polarisation that threatens the credibility of research. Scientists can even apply marketing techniques to reach the majority of people (Wright et al. 2015, Redford et al. 2015). Knowledge from social-psychological science helps to mainstream nature conservation (van Vugt 2009). In these regards, conservation biogeographers should actively and adequately promote protected areas as a solution to various environmental problems (Dinerstein et al. 2019, MacKinnon et al. 2011) since protected areas safeguard biodiversity, ecosystem functioning and multiple ecosystem services, which strengthen human well-being and represent various values of nature.

Protected areas decrease habitat degradation (Geldmann et al. 2013, Joppa and Pfaff 2010) and maintain species and populations better than other conservation measures (Geldmann et al. 2013, Karanth et al. 2009, Taylor et al. 2011, Laurance et al. 2012, Walston et al. 2010, Hilborn et al. 2006). Biodiversity is higher inside protected areas than in their surroundings (Coetzee et al. 2014, Gray et al. 2016), while they cannot halt the loss completely (Rada et al. 2019, Dähler et al. 2019, Laurance et al. 2012, Geldmann et al. 2019, Leberger et al. 2019, Heino et al. 2015). Protected areas are especially effective for global biodiversity conservation if they are actively managed, well-funded (Geldmann et al. 2018, Coad et al. 2019) and located in biodiversity-rich areas (Joppa et al. 2013). Protected areas remain effective in preserving species despite climate change (Beale et al. 2013, Virkkala et al. 2019, Lehikoinen et al. 2019, Santangeli et al. 2017, Lawson et al. 2014). They provide ecosystem services, e.g. climate change mitigation and adaptation (MacKinnon et al. 2011, Soares-Filho et al. 2010, Scharlemann et al. 2010), natural catastrophe control and the provision of habitat and natural resources (Postel and Thompson 2005, Palomo et al. 2013, Xu et al. 2017), tourism and recreation (Balmford et al. 2009) and poverty reduction (Andam et al. 2010). Moreover, the global protected area estate expands (Bingham et al. 2019).

If the global protected area extent grew to half of the terrestrial area on earth, new protected areas would have to be wisely planned to stop biodiversity loss (Pimm et al. 2018, Montesino Pouzols et al. 2014) and meet human demands simultaneously (Ellis and Mehrabi 2019). Protected area expansion is, however, challenging because land is increasingly modified and used for human purposes only (Sala 2000), which emphasises the need for nature conservation outside protected areas. A high degree of biodiversity can exist outside protected areas. Some species are even restricted to unprotected areas (Rodrigues et al. 2004), e.g. in Canada (Deguise and Kerr 2006) and in the Mediterranean biome (Cox and Underwood 2011). Species migrating between protected areas also depend on unprotected areas (Troupin and Carmel 2014). Furthermore, established protected areas are often taken as justification for environmental degradation in the protected area surroundings (McNeely et al. 1990, Radeloff et al. 2010, Hellwig et al. 2019). If biodiversity is lost outside protected areas, this will have, in turn, consequences for the biodiversity inside (Laurance et al. 2012, Rada et al. 2019). The smaller a protected area is, the more it is affected by unprotected surroundings (Yamaura et al. 2008). Consequently, nature conservation outside protected areas is essential as well.

The sustainable use of unprotected land can complement protected areas in conserving biodiversity (Locke et al. 2019), e.g. by applying low-intensity agriculture and forestry (Kremen and Merenlender 2018). Land sharing (i.e. sharing agricultural land with conservation efforts) and land sparing (i.e. temporally sparing agricultural land for conservation) are two strategies to merge agricultural practices and biodiversity conservation in cultural landscapes (Baudron and Giller 2014). Private land can also be dedicated to biodiversity conservation by voluntary conservation efforts, e.g. in private gardens (Farmer et al. 2017). Such efforts refer to other effective area-based conservation measures (OECMs), which are essential complements to protected areas for reaching global conservation targets (Dudley et al. 2018, Frascaroli et al. 2019).

There are numerous signs of general conservation success. Conservation efforts have, for instance, decreased the extinction risk of mammals and birds in 109 countries by 29% from 1996 to 2008 (IPBES 2019); the average extinction risk of birds, mammals and amphibians would have been at least 20% higher without conservation initiatives; more than 107 highly threatened birds, mammals and reptiles took profit from the conservation-minded eradication of invasive mammals on islands. Many endangered species are recovering (IUCN 2019). Moreover, many people do perceive nature conservation as a priority (Varma et al. 2015). Public media and institutions such as zoos, museums and botanical gardens, increasingly provide conservation-minded education programmes (Miller et al. 2004). Markets for green and sustainable products have been growing enormously (Steinemann et al. 2017). The economic value of nature is more often incorporated into economics and policy, which supports nature conservation (Reyers et al. 2013, Kubiszewski et al. 2013, Bateman et al. 2013, Waldron et al. 2017). Policy-makers increasingly discontinue perverse subsidies to environmentally harmful businesses (Merckx and Pereira 2015). The members of the European Parliament call for legally binding biodiversity targets, equivalent to the Paris agreement on climate change (European Parliament 2019). Cornerstone for more sustainable future policies in nature conservation would be financial and economic systems refusing the contemporary paradigm of economic growth (Díaz et al. 2019). Nevertheless, current rates of global biodiversity loss are alarming (IPBES 2019). Consequently, large-scale conservation planning is still essential and should be prioritized in policy decisions.

The societal and political values that people assign to nature are eventually decisive for nature conservation. Informed by conservation biogeographers and other experts, the societal willingness can prompt stakeholders, policy-makers and governments to induce transformative changes required for global nature conservation and sustainable development. In the future people may perceive the first decades of the 21st century as the starting point for a very successful period of nature conservation (Sodhi et al. 2011), initiated by young people, such as those involved in the movements of Fridays for Future all over the world. However, societal trends are fickle. The task of conservation biogeographers continuously communicating their work to the people is accordingly all the more important to ensure an enduring public support for nature conservation. Conservation biogeographers are able to produce comprehensive and integrative knowledge about our relationship to nature. They will be more successful in converting this knowledge into policy and practice if they also try to communicate the values of nature persistently.

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