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## CONTRIBUTED PAPER

# Coupling future climate and land-use projections reveals where to strengthen the protection of Mediterranean Key Biodiversity Areas

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## Abstract

Identifying sites that are both important for biodiversity and likely to be heavily affected by anthropogenic pressures in the future is crucial to settle priorities in the implementation of conservation measures, such as the designation of new protected areas. Although assessing the exposure of terrestrial Key Biodiversity Areas to global change would support such identification, it has never been performed to our knowledge. In addition, previous exposure assessments have been limited to few metrics of climate change and have not considered other global change components. Here, we assess the extent to which terrestrial (including inland water) Key Biodiversity Areas are exposed to future climate change and land-use modifications in 29 countries of the Mediterranean region, and identify countries where additional protection efforts are most needed. To this end, we calculated two local and two regional exposure metrics using projections of climate and land-use for late 21<sup>st</sup> century under four scenarios that were used in the sixth assessment report of the Intergovernmental Panel on Climate Change (SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5). These four exposure metrics were subsequently combined into an exposure index ranking sites from least to most exposed to climate and land-use changes. We highlight that the most exposed non-protected Key Biodiversity Areas are located in countries where the protection of this network is lowest (i.e., high number and percentage of non-protected sites). We also found that Key Biodiversity Areas were overall more exposed than the rest of the study zone and that the sites most in need of conservation actions were similar across future scenarios. Our study reinforces the pressing necessity to strengthen and extend conservation measures in Mediterranean Key Biodiversity Areas, especially in Middle-East and Maghreb countries whose Key Biodiversity Areas are both at risk to be strongly affected by anthropogenic pressures and insufficiently protected.

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## KEYWORDS

climate change, climate velocity, CMIP6, conservation planning, exposure assessment, land-use modifications, protected areas, sites of importance for biodiversity, spatial prioritization

## 1 | INTRODUCTION

Human activities are threatening ecosystems and species through different pressures (e.g., habitat destruction and degradation, climate change) of spatially heterogeneous intensity (Sanderson et al., 2002). As biodiversity is also not evenly distributed in space at a global scale (Gaston, 2000), examining the spatial overlap between biodiversity and its threats has allowed conservationists to develop different approaches to identify areas to prioritize for the allocation of conservation resources over the last decades (Brooks et al., 2006). Reactive approaches of prioritization for instance, such as the biodiversity hotspot network, integrate regions that are both important for biodiversity conservation and heavily affected by ongoing global change (Brooks et al., 2006; Myers et al., 2000).

It is also critical to identify sites of importance for biodiversity that are likely to be heavily affected by global change in the next decades and support their prioritization in the implementation of conservation measures (Joppa & Pfaff, 2009). Anticipating the future location and magnitude of anthropogenic threats by assessing the exposure of sites of importance for biodiversity to global change would enable such identification. Drawing on the definition of exposure to climate change found in Dawson et al. (2011), we define here the exposure of a site as the extent of changes in environmental conditions (e.g., temperature, precipitation, habitat loss, and degradation) likely to be experienced by the site and that depends on the rate and magnitude of changes. This approach can integrate multiple anthropogenic pressures and also multiple metrics that can account for different responses of species to climate change, that is, local adaptation and range shift (Garcia et al., 2014).

Land-use modifications are one of the most important historical drivers of biodiversity loss and will continue to be in the next decades (IPBES, 2019; Millennium Ecosystem Assessment, 2005; Newbold, 2018; Newbold et al., 2015; Sala, 2000). Including land-use changes when assessing the future effects of global change on biodiversity is thus critical. However, very few exposure assessments are based on future land-use projections (but see Wilson et al. [2014] and Holman et al. [2017]), in line with previous literature reviews (de Chazal & Rounsevell, 2009; Santos et al., 2021; Titeux et al., 2016), whereas most studies have used future projections of climate (e.g., Hoffmann et al., 2019; Lapola et al., 2020;

Scriven et al., 2015). This trend may be a result of the many limitations of future projections of land-use (Harfoot et al., 2014; Titeux et al., 2016). Previous assessments of exposure to climate change have also tended to focus on a single exposure metric and have therefore not considered the different responses of biodiversity to climate change (Garcia et al., 2014). This is of particular concern for the identification of sites that could be strongly affected by global change, since different global change components and exposure metrics might be spatially distributed in different ways in coming decades (Garcia et al., 2014).

The exposure to anthropogenic threats might also depend on the future socioeconomic trend of society and greenhouse gas emissions (IPBES, 2016; IPCC, 2021). Exposure assessments should hence consider a range of plausible futures by using different exploratory scenarios, such as the CMIP6 scenarios that cover a wide range of socioeconomic and climatic conditions by the end of the 21<sup>st</sup> century (O'Neill et al., 2016). Yet many exposure assessments used only two scenarios or less to date.

Key Biodiversity Areas (KBAs) are “sites contributing significantly to the global persistence of biodiversity” where conservation measures should be implemented (Eken et al., 2004; IUCN, 2016; Margules & Pressey, 2000). They are identified using threshold-based criteria of, *inter alia*, vulnerability, and irreplaceability, that can be applied to any ecosystem and macroscopic species and are available in a global database (BirdLife International, 2020). Protected areas (PAs, see the definition in Dudley [2008]) are one of the most important tools employed by current conservation strategies. They can have better “conservation outcomes” (e.g., population trends) than non-protected sites (Coetzee et al., 2014; Gray et al., 2016) through reducing threats and enhancing resilience to anthropogenic pressures (Rodrigues & Cazalis, 2020). For instance, PAs play a critical role in climate change mitigation (see Thomas & Gillingham, 2015 for a review) and can reduce habitat destruction (Geldmann et al., 2013; Leberger et al., 2020).

Because of the key role of PAs in the context of global change, the United Nations Convention on Biological Diversity (CBD) set an objective of 17% of terrestrial land surface area protected by 2020 (CBD, 2010). Unfortunately, this target was not met in time as only 15% of terrestrial land surface areas was protected in 2020 (Stokstad, 2020). Moreover, criteria for designation often included limited accessibility and low economical interest

rather than particular importance for biodiversity *per se* (Butchart et al., 2012; Joppa & Pfaff, 2009; Venter et al., 2018). As a result, only 19.2% of terrestrial (including inland water) KBAs are fully within PAs worldwide (UNEP-WCMC & IUCN, 2021). New targets recently set by the CBD advocate for countries to protect 30% of their area by 2030 (CBD, 2020). These even more ambitious targets provide a major opportunity to ensure that the future PAs network covers sites of importance for biodiversity, and especially those that are at risk to be heavily affected by global change in the next decades (Joppa & Pfaff, 2009). Although their identification can be achieved by assessing the exposure of KBAs, such assessment has never been performed for terrestrial KBAs to our knowledge, as exposure assessments mainly focused on PAs.

Identifying sites of importance for biodiversity for the designation of new PAs is of particular interest in the Mediterranean region, where ecosystems have been affected by human activities for thousands of years, leading for example to the loss of more than 95% of its primary vegetation (Myers et al., 2000). More recently, drivers of global change have worsened with, for example, human population growth, mass tourism development, overexploitation of water resources, conflicts and overall weak governance to conserve biodiversity (UNEP/MAP & Plan Bleu, 2020), and this region has experienced climate warming 0.4°C above the global average warming since preindustrial period (MedECC, 2020). These drivers and pressures are heterogeneously distributed, with environmental conditions deteriorating more in the east and south of the region, and are likely to worsen in the next decades, with the potential intensification of land management (Malek et al., 2018) and a severe aridification over the Sahara and Iberian Peninsula (Drobinski et al., 2020). Nevertheless, the Mediterranean basin remains a particularly important biodiversity hotspot for plants (Myers et al., 2000), but also for many other taxonomic groups, with very high species richness and endemism rates (CEPF, 2017).

In this study, we evaluated for the first time the exposure of terrestrial (including inland water) KBAs to future climate change and land-use modifications. This exposure assessment was performed on the Mediterranean region (29 countries), where KBAs were comprehensively identified. Our primary goal was to identify countries where KBAs are highly exposed and still lack a strong protection status in order to support their prioritization in the designation of new PAs. To this end, we calculated two local and two regional exposure metrics and three synthetic exposure indices from late 21<sup>st</sup> century (2081–2100) projections of climate and land-use under four of the most recent scenarios (O'Neill et al., 2016), which makes this exposure assessment one of the most comprehensive to date. As new land protection objectives are about to be set, the

results from this study can help guide the implementation of conservation measures such as the designation of new PAs in the Mediterranean region, where biodiversity is among the most sensitive to land-use and climate changes on the planet (Newbold et al., 2020).

## 2 | METHODS

### 2.1 | Study zone

This study was carried out on the administrative boundaries of 29 countries around the Mediterranean basin without: overseas territories (e.g., overseas France, the Azores) and large areas of “Desert and Xeric Shrublands” (Olson et al., 2001), as well as small and isolated patches of “Flooded Grasslands and Savannas” (Figure 1 and Appendix S1). The definitive study zone covered 3,814,480 km<sup>2</sup> and encompassed the Mediterranean basin biodiversity hotspot (Myers et al., 2000). The study zone was rasterized to a 15 arc-min resolution (approx. 770 km<sup>2</sup> at the equator) to match land-use spatial resolution.

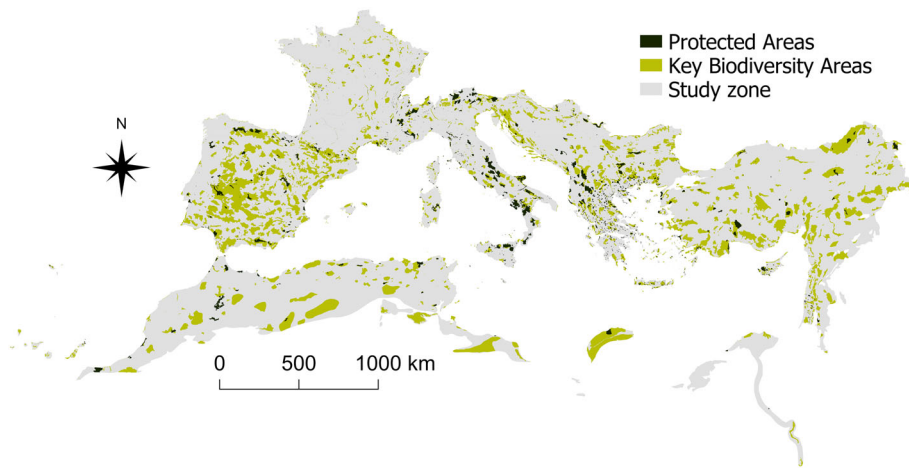
### 2.2 | Key Biodiversity Areas

KBAs boundaries were extracted from the World Database of KBAs (BirdLife International, 2020). We used the term “KBAs” to refer to sites with different statuses: KBAs *stricto sensu* (Eken et al., 2004) as well as sites designated as part of previous networks, that is, Important Bird and Biodiversity Areas (IBA, BirdLife International, 2014) and Alliance for Zero Extinction sites (AZE, Ricketts et al., 2005). Many sites combined multiple statuses (e.g., IBA and KBA, Appendix S2).

After excluding marine parts of KBAs, 2271 sites covering 18.9% of the study zone were selected (Figure 1). In order to compare the exposure of KBAs with that of the rest of the study zone, we defined as “KBA cell” any study zone cell whose surface area covered by KBAs was higher than 40%. This threshold was selected following D'Amen et al. (2011), that is, by choosing a threshold that resulted in a total surface area of KBA cells similar to the initial total surface area of KBAs. Accordingly, we defined 1111 KBA cells intersecting 902 KBAs (39.7% of the study zone KBAs). All other study zone cells (6042 cells) were referred to as “non-KBA cells.”

### 2.3 | Protected Areas

PAs boundaries were extracted from the Mediterranean Wetlands Observatory database. This database is the most



**FIGURE 1** Map of the study zone with Key Biodiversity Areas and protected areas.

up-to-date PAs database available for the study zone, as it combines information from multiple international sources such as the World Database of Protected Areas (WDPA, UNEP-WCMC & IUCN, 2020), the Nationally designated areas database (CDDA) and designated sites under international agreements (e.g., the Ramsar Convention, Natura 2000), complemented with systematic national inventories. We selected the 7454 PAs of IUCN category I–IV as these PAs have more restrictive management than PAs of IUCN category V and VI (Dudley, 2008) and are thus more likely to reduce the exposure to global change.

These PAs covered 94,589 km<sup>2</sup> (2.5% of the study zone) and were mostly located in KBAs (66,965 km<sup>2</sup>, 70.8% of the PAs total surface area, 9.3% of the KBAs total surface area). One-third of KBA cells (358 cells, 32.2%, hereafter referred to as “protected KBA cells,” as opposed to “non-protected KBA cells”) overlapped PAs (i.e., proportion of area covered by PAs greater than 0%), although the proportion of protected KBA cells highly differed between countries (Appendix S3). PAs coverage of protected KBA cells was very low (mean = 18.7%, median = 11.5%).

## 2.4 | Environmental data

To assess the differences between near-current (1970–2000 period) and future (2081–2100 period) temperature and precipitation conditions, we used seven bioclimatic variables (Figure 2) previously used in similar studies (e.g., Batllori et al., 2017; Carroll et al., 2017; Parks et al., 2020) from the WorldClim 2.1 dataset (Fick & Hijmans, 2017) and illustrating the annual trend, seasonality and seasonal extremes: annual mean temperature, maximum temperature of warmest month, minimum temperature of coldest month, temperature annual range,

annual precipitation, precipitation of wettest quarter, and precipitation of driest quarter. We used future projections from the eight General Circulation Models (GCMs) available to date in the WorldClim 2.1 database (GCMs description is provided in Appendix S4) under four scenarios (see below).

We assessed land-use modifications between the same periods, using a yearly estimate of the proportion of 12 land-use categories at a 15 arc-min spatial resolution (approx. 28 × 28 km at the equator) for year 1985 and 2090 (Figure 2 and Appendix S5) from the Land Use Harmonization 2 dataset (Hurtt et al., 2020). This dataset was developed to link historical land-use and future land-use projections produced by Integrated Assessment Models (IAMs, Harfoot et al., 2014). These land-use projections were also developed to be used as input for modeling the future climate projections that were described above (Hurtt et al., 2020). To our knowledge, this is the only dataset that provides future land-use projections both at global scale and under the latest scenarios (see below).

Bioclimatic variables were mean-aggregated from their original spatial resolution (5 arc-min) to land-use data resolution. Both climate and land-use spatial data were reprojected at a 634 km<sup>2</sup> resolution (approx. 23 km × 28 km) using Lambert Azimuthal Equal Area centered on the study zone.

## 2.5 | Future scenarios

We used the same four scenarios of the Coupled Model Intercomparison Project phase 6 (CMIP6, Eyring et al., 2016) for future projections of both climate and land-use: SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5 (Appendix S6). Each scenario is the combination of a socioeconomic component (Shared Socioeconomic Pathway: SSP, O'Neill et al., 2014) and a radiative forcing level

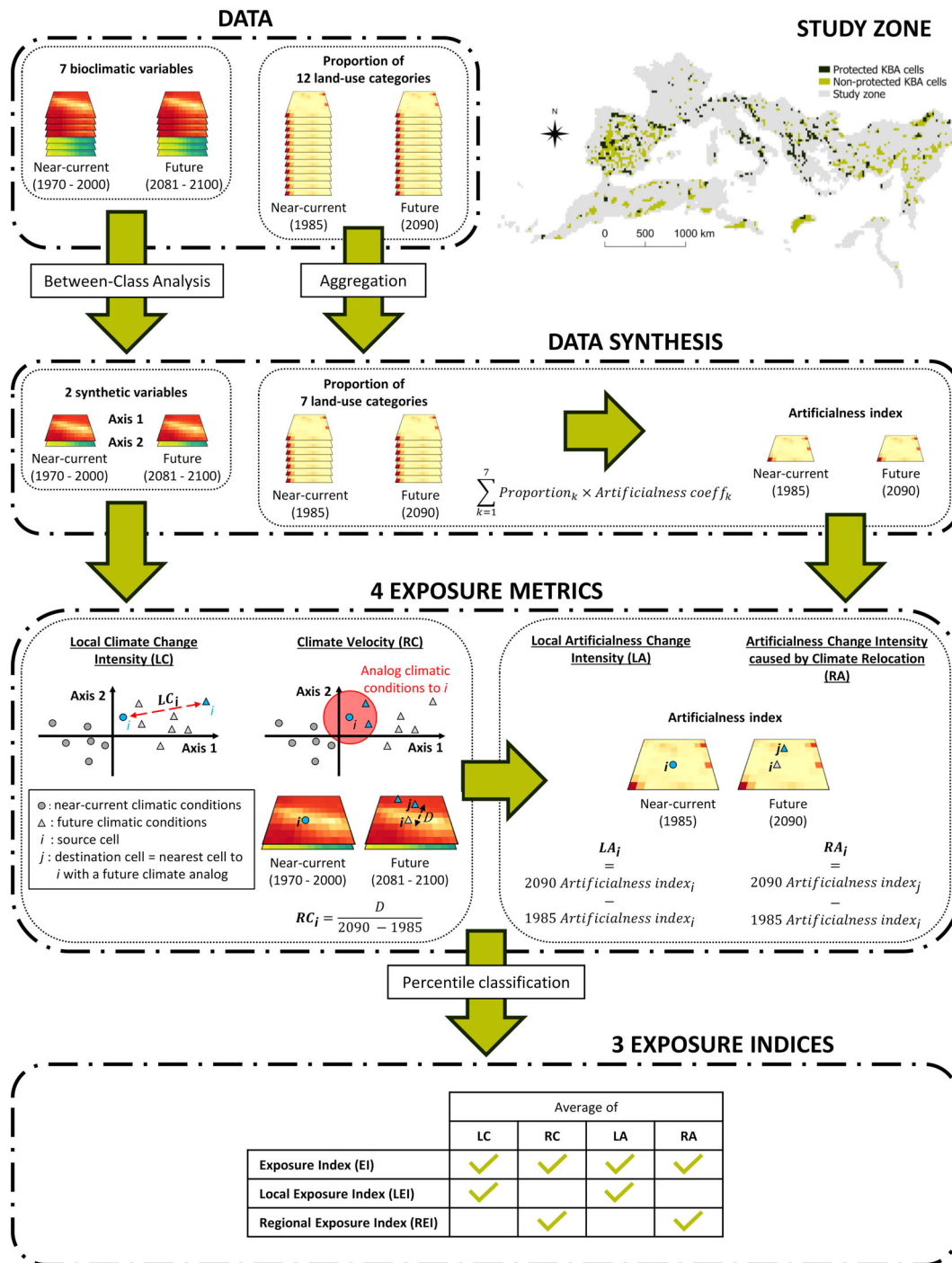


FIGURE 2 Description of all methodology steps performed using future projections from one of the eight General Circulation Models (GCMs) and in one of the four scenarios.

in 2100 (Representative Concentration Pathway: RCP: 2.6–8.5, van Vuuren et al., 2011).

The SSP1-2.6 scenario features a more sustainable society and a low radiative forcing (warming between 1.3 and 2.4°C by 2100, IPCC, 2021). SSP2-4.5 describes a world that does not “shift markedly from historical patterns” combined with a medium level of radiative forcing (warming between 2.1 and 3.5°C by 2100).

SSP3-7.0 is characterized by regional conflicts, the absence of new climate policies and a high radiative forcing (warming between 2.8 and 4.6°C by 2100). Lastly, SSP5-8.5 is an unmitigated scenario that features an important technological progress and fossil fuel exploitation associated with a very high level of radiative forcing (warming between 3.3 and 5.7°C by 2100).

## 2.6 | Climate change analysis

To summarize the climatic differences between the near-current period and future scenarios and address the correlations between variables, we performed for each GCM a Between-Class Analysis (BCA) on the seven bioclimatic variables (Figure 2) using the *ade4* package (Dray & Dufour, 2007).

In order to evaluate the exposure of KBAs to climate change, we then calculated two exposure metrics that are complementary (Garcia et al., 2014) from the two axes of the BCA for each study zone cell (Figure 2): the local climate change intensity and the climate velocity (Hamann et al., 2015). The local climate change intensity is a local measure of climate change (hereafter referred to as “LC”), whereas the climate velocity is a regional measure of climate change (hereafter referred to as “RC,” Garcia et al., 2014). Indeed, LC was the Euclidian distance in the two-dimensional climate space (defined by the axis 1 and axis 2 of the BCA) between each cell's near-current and future climates and thus describes the intensity of change in temperature and precipitation conditions at a local scale (in BCA units). On the other hand, RC was based on forward velocity (Hamann et al., 2015), an analog-based climate velocity that represents the relocation speed of climatic conditions (Carroll et al., 2015; Hamann et al., 2015). To compute RC in  $\text{km year}^{-1}$ , we measured the geographical distance between a near-current raster cell (hereafter referred to as “source cell”) and its nearest future climate analog (hereafter referred to as “destination cell”) using the *geosphere* package (Hijmans, 2019), and divided it by the time period between near-current and future data (i.e., 105 years). Further information on the definition of analog climates is provided in Appendix S7. When the source cell was a KBA cell, its nearest future climate analog (i.e., the destination cell) was referred to as “KBA refuge.”

## 2.7 | Land-use modifications analysis

We computed an artificialness index to synthesize the intensity of anthropogenic land-use modifications between future scenarios (year 2090) and near-current period (year 1985). Artificialness is an antonym of “naturalness” that can be considered as a conservation value and a priority for conservation planning (Angermeier, 2000; Machado, 2004). We first aggregated the 12 land-use categories into seven classes (Figure 2 and Appendix S5) as several categories could not be differentiated by their naturalness following the guidelines provided in Machado (2004): urban land, annual crops, perennial crops, managed pastures, rangeland, secondary land, and primary land. We then assigned to each

class a naturalness coefficient ranging from 0 to 10 following Machado (2004), subtracted it from 10 to compute the artificialness coefficient, and then computed the sum of each land-use class proportion weighted by its artificialness coefficient (Appendix S5).

In order to evaluate the exposure of KBAs to anthropogenic land-use modifications, we calculated two complementary exposure metrics from the artificialness index (Figure 2): the local artificialness change intensity and the artificialness change intensity caused by climate relocation. If we apply the classification of climate change measures of Garcia et al. (2014) to land-use changes measures, we can consider the local artificialness change intensity as a local measure of artificialness change (hereafter referred to as “LA”) and the artificialness change intensity caused by climate relocation as a regional measure of artificialness change (hereafter referred to as “RA”). Indeed, LA describes the intensity of change in artificialness at a local scale, as for raster cell  $i$ , it was calculated as the difference between the artificialness index of cell  $i$  for year 2090 and that for year 1985. On the other hand, RA describes the difference in artificialness between future and current locations with similar climatic conditions. For raster cell  $i$ , it was calculated as the difference between the artificialness index of the destination cell  $j$  for year 2090 and that of the source cell  $i$  for year 1985.

## 2.8 | Combining exposure metrics

In order to assess the exposure to both climate change and anthropogenic land-use modifications of a KBA cell compared with other KBA cells within the same scenario, we combined the exposure metrics into three complementary composite indices at different spatial scales (Figure 2): the local exposure index (LEI), the regional exposure index (REI), and the exposure index (EI), which is the relative exposure to climate and land-use changes at both local and regional scales. The exposure index (EI) was computed as the average rank between the four exposure metrics, LEI from LC and LA, and REI from RC and RA, after classifying each metric into 100 groups using percentiles as thresholds.

## 2.9 | Data analysis

We assessed the exposure of KBAs using exposure metrics and indices in order to identify the sites of importance for biodiversity that are likely to be the most affected by climate change and land-use modifications, and to prioritize them to be targeted by conservation measures.

For each scenario, we compared the exposure between KBA cells and non-KBA cells, and between protected and non-protected KBA cells, using Wilcoxon rank sum tests (Wilcoxon, 1992). We also compared geographic patterns of exposure between scenarios and between metrics using Kendall's rank correlation tests (Kendall, 1948). Finally, we evaluated the difference in KBA cells exposure between scenarios for each exposure metric using Wilcoxon signed-rank tests (Wilcoxon, 1992). National averages of exposure metrics and indices were also compared between countries. Note that we also evaluated the relationship between exposure and elevation using data from the Shuttle Radar Topography Mission (SRTM, Farr et al., 2007) and Kendall's rank correlation tests (Kendall, 1948).

Statistical analyses were performed on the average multi-model of a future scenario based on the eight GCMs for all exposure metrics and indices except LA. Statistical analyses and geoprocessing operations were performed using R 3.6.2 (R Core Team, 2019) and QGIS 3.4.15 (QGIS Development Team, 2020). Statistical significance was set at  $p < 0.05$ .

## 3 | RESULTS

### 3.1 | Differences in exposure between KBAs and non-KBAs

KBA cells were overall located at higher elevations than non-KBA cells and had lower values of near-current artificialness index (Appendix S8). Differences between KBA cells and non-KBA cells were found for all near-current bioclimatic variables except for annual precipitation and precipitation of driest quarter (Appendix S8).

KBA cells were overall more exposed than non-KBA cells: they had higher values of exposure in 13 cases out of 16 (LC, RC and RA in all scenarios, and LA in SSP1-2.6, Figure 3, Appendix S8), whereas no differences were found for the three last cases (LA in SSP2-4.5, SSP3-7.0, and SSP5-8.5, Figure 3, Appendix S8).

### 3.2 | Differences in exposure between metrics and indices

Maps of exposure metrics of KBA cells under each scenario are provided in Appendix S9 and S10. The four exposure metrics were overall very weakly correlated in KBA cells (Mean absolute value of Kendall's Tau = 0.15, Appendix S11) except for the two land-use modifications exposure metrics (i.e., LA and RA) that had much more similar geographic patterns (Kendall's Tau comprised

between 0.43 and 0.52, Appendix S9). On the other hand, LEI and REI had a weak positive correlation (Kendall's Tau comprised between 0.25 and 0.32, Appendix S9). Few KBA cells (less than 5%, Appendix S12) featured high values of LEI and low values of REI or *vice versa*. Nevertheless, Turkish KBA cells had overall higher LEI values than REI, whereas KBA cells in Maghreb countries (i.e., Algeria, Morocco, Tunisia, and Libya) and mountainous areas had mostly higher values of REI than LEI (Appendix S12 and S13).

### 3.3 | Differences in average exposure between scenarios

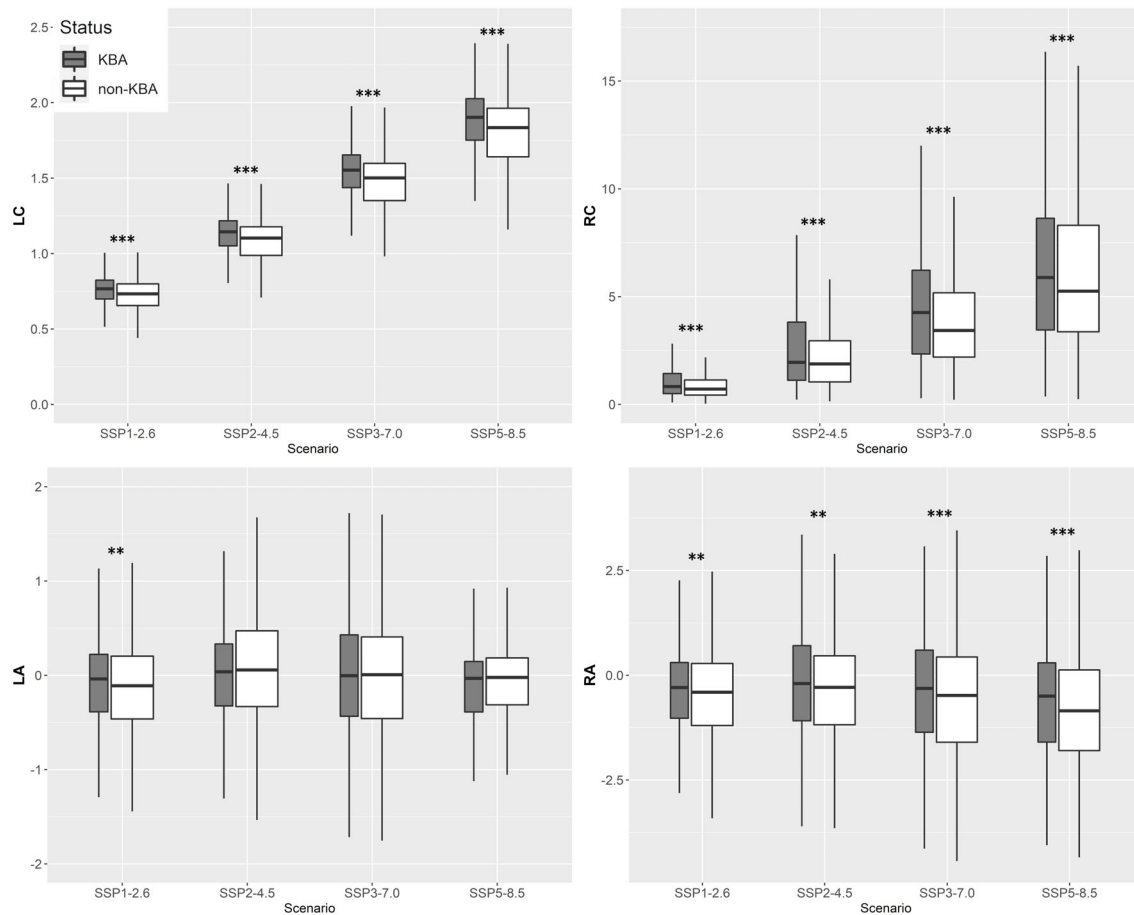
The average values of climate change exposure metrics (i.e., LC and RC) in KBA cells were very different between scenarios and increased with the radiative forcing level (Figure 3 and Appendix S14). KBA cells without future climate analog were mostly located in north-eastern Turkey and in the Alps and their number increased with the radiative forcing level (Appendix S9) although remaining very low (SSP1-2.6:  $n = 3$ , 0.27%; SSP2-4.5:  $n = 7$ , 0.63%; SSP3-7.0:  $n = 21$ , 1.89%; SSP5-8.5:  $n = 27$ , 2.43%).

Differences between scenarios were overall less pronounced for land-use modifications exposure metrics (i.e., LA and RA) in KBA cells than for climate change exposure metrics and their values did not increase with the radiative forcing level (Figure 3 and Appendix S14). LA was highest in SSP2-4.5, driven by an important decrease of primary land especially in Turkey, and lowest in SSP5-8.5 due to an increase in secondary land and a decrease in annual crops especially in north-west Africa (Appendix S10 and S14). Values of RA were lower than zero for most KBA cells in all scenarios (Figure 3), meaning that KBA refuges had overall a projected future artificialness index lower than the near-current artificialness index of KBA cells.

### 3.4 | Differences in geographic patterns of exposure between scenarios

Overall, a given exposure metric or index had similar geographic patterns in KBA cells regardless of the scenario. Exposure of KBA cells in SSP2-4.5, SSP3-7.0, and SSP5-8.5 were strongly and positively correlated for all metrics and indices (Kendall's Tau comprised between 0.51 and 0.91, Figure 4, Appendix S9, S10, and S15). Exposure in SSP1-2.6 was less correlated to the exposure in SSP2-4.5, SSP3-7.0, and SSP5-8.5, but their geographic patterns were still fairly similar (Mean Kendall's





**FIGURE 3** Comparison of local measure of climate change (LC; top left), regional measure of climate change (RC; top right), local measure of artificialness (LA; bottom left), and regional measure of artificialness (RA; bottom right) between Key Biodiversity Area (KBA) cells (in gray) and non-KBA cells (in white) under each scenario. Box widths are proportional to the number of observations (square root-transformed) in the groups. Outliers are not displayed. \* $p < .05$ ; \*\* $p < .01$ ; \*\*\* $p < .001$ .

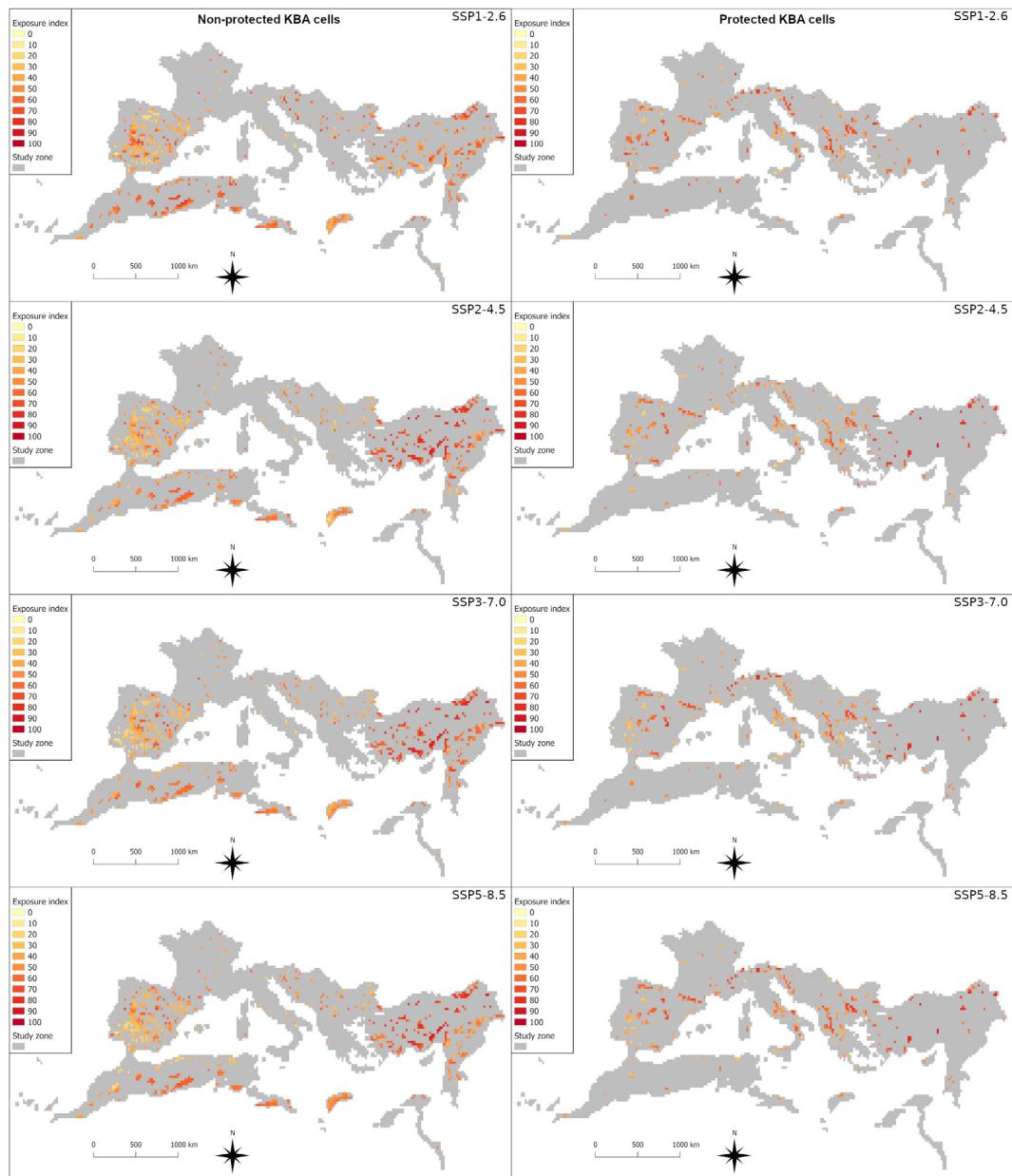
Tau = 0.45, Appendix S9, S10, and S15). The differences in geographic patterns of EI between scenarios were probably mainly driven by the two land-use modifications exposure metrics (LA and RA) and the regional climate change exposure metric (RC), as patterns of LC were extremely similar between scenarios (Mean Kendall's correlation rank tau = 0.87, Appendix S15).

Under SSP5-8.5, the highest values of LC were found in KBA cells of Balkan countries and Turkey, while the highest values of RC were found in Maghreb and Middle-East countries (Table 1). Middle-East countries had the highest values of LA (Table 1), mainly driven by urbanization and a loss of primary land in SSP5-8.5. Strongly negative values of LA were found in Balkan countries, because of the conversion of pastures and annual crops into secondary land, and in Morocco in SSP5-8.5 (Table 1). Positive values of RA were only found in Cyprus, Tunisia, and Turkey and lowest values of RA were found in Balkan countries in SSP5-8.5 (Table 1).

Turkish KBA cells displayed the highest values of EI in all scenarios except for SSP1-2.6 (Figure 4, Appendix S13). KBA cells in other Middle-East countries, such as in Egypt and Lebanon, and in the Alps were also highly exposed in these three scenarios whereas the pattern was less clear for SSP1-2.6 (Figure 4 and Appendix S13). In contrast, KBA cells in some countries of Western Europe (Portugal, Italy, and Spain) and the Balkans (Bosnia and Herzegovina and Montenegro) had overall low values of EI (Figure 4 and Appendix S13). We also found a positive correlation between exposure metrics and elevation in all scenarios except for LA in SSP1-2.6 (Appendix S16).

### 3.5 | Exposure of non-protected KBAs

Turkish non-protected KBA cells, which were highly abundant, were the most exposed in three scenarios (SSP2-4.5, SSP3-7.0, and SSP5-8.5, Figures 4 and 5). As a result, among



**FIGURE 4** Exposure index of non-protected Key Biodiversity Area (KBA) cells (left) and protected KBA cells (right) under each scenario (see Appendix S17 for a representation of the exposure index variability between General Circulation Models [GCMs]).

the 100 KBA cells with the highest EI, more than 96% of the non-protected ones were located in Turkey in three scenarios (SSP1-2.6: 40.7%, SSP2-4.5: 97.3%, SSP3-7.0: 100%, and SSP5-8.5: 96.9%). Non-protected KBA cells in Tunisia, Egypt, and Lebanon were also highly exposed (Figure 5).

Non-protected KBA cells were overall less exposed than protected KBA cells in two scenarios (SSP1-2.6 and SSP5-8.5) and no overall differences were found for SSP2-4.5 and SSP3-7.0 (Appendix S18). However, these differences highly varied between countries (Figure 5). For instance, Maghreb countries such as Algeria, Morocco, and Libya, which had a large number and proportion of

non-protected KBA cells, had overall higher values of EI in non-protected KBA cells than in protected KBA cells (Figure 5). In contrast, many countries from Western Europe and the Balkans (e.g., Italy, France, Bulgaria, North Macedonia, and Slovenia), which had a low number and proportion of non-protected KBA cells, had overall lower values of EI in non-protected KBA cells than in protected KBA cells (Figure 5). Furthermore, the exposure of non-protected KBA cells in these countries was usually low (Figure 5). Non-protected KBA cells of Spain, which were the most abundant, were not highly exposed and were less exposed than protected KBA cells.

**TABLE 1** Country averages of local measure of climate change (LC; in BCA units), regional measure of climate change (RC; in km year<sup>-1</sup>), local measure of artificialness (LA; in artificialness index), and regional measure of artificialness (RA; in artificialness index) in Key Biodiversity Area (KBA) cells under the SSP5-8.5 scenario

Country	LC	RC <sup>a</sup>	LA	RA <sup>a</sup>
Albania	<b>2.06</b>	5.37	0.25	-0.72
Algeria	1.84	6.65	-0.33	-1.04
Bosnia and Herzegovina	<b>2.00</b>	4.66	-0.75	-2.57
Bulgaria	2.00	6.85	-0.18	-1.13
Croatia	1.96	2.85	-0.02	<b>0.00</b>
Cyprus	1.30	7.08	-0.04	<b>0.81</b>
Egypt	1.44	<b>14.16</b>	<b>1.26</b>	<b>-0.01</b>
France	1.82	3.99	0.09	-0.52
Greece	1.92	6.58	-0.12	-1.08
Israel	1.54	<b>11.43</b>	<b>0.61</b>	-1.01
Italy	1.85	5.82	-0.16	-0.82
Jordan	1.66	7.29	<b>0.46</b>	-1.10
Lebanon	1.61	<b>7.81</b>	<b>0.71</b>	-1.13
Libya	1.50	<b>12.91</b>	0.14	-0.46
Montenegro	<b>2.06</b>	6.06	-0.76	-1.84
Morocco	1.69	<b>10.20</b>	-0.83	-0.69
North Macedonia	<b>2.11</b>	4.90	-0.32	-1.62
Portugal	1.60	4.34	-0.01	-0.23
Serbia	<b>2.06</b>	6.01	-0.51	-1.61
Slovenia	1.91	1.89	-0.12	-0.13
Spain	1.90	6.02	-0.42	-0.97
Syria	1.79	5.10	0.14	-1.20
Tunisia	1.83	3.37	0.21	<b>0.91</b>
Turkey	1.99	6.12	<b>0.36</b>	<b>0.12</b>

Note: The five highest values are in bold. Country averages and standard deviations for exposure indices (LEI, REI, and EI) and under other scenarios (SSP1-2.6, SSP2-4.5, and SSP3-7.0) are provided in Appendix S13.

<sup>a</sup>KBA cells without a future climate analog were excluded.

## 4 | DISCUSSION

This first exposure assessment of terrestrial KBAs carried out using an innovative framework combining future projections of climate and land-use highlighted that Mediterranean KBAs were overall more exposed to climate change and land-use modifications than sites of lesser importance for biodiversity. We also found that geographic patterns of exposure were overall very similar between future scenarios. Countries with the most exposed non-protected KBAs were also those with the lowest protection of KBAs, reinforcing the necessity to

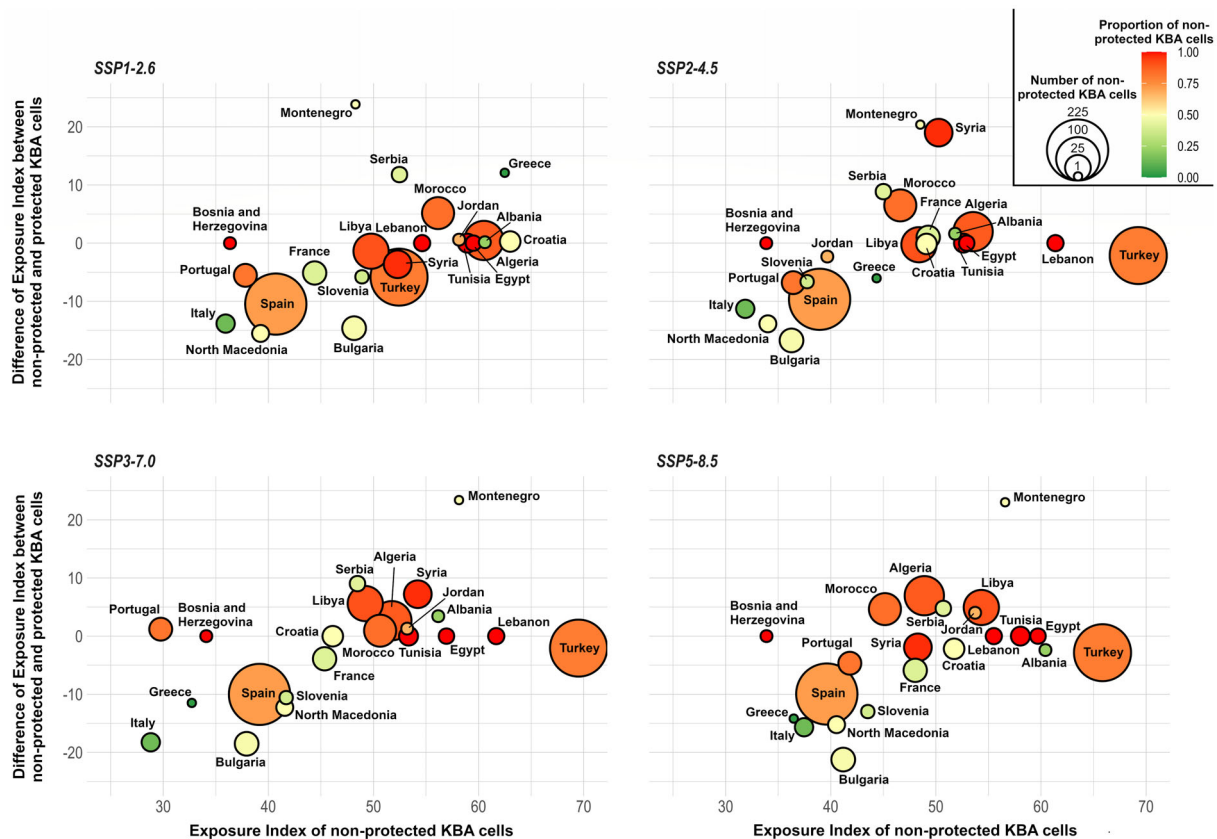
strengthen the protection of this network of sites of importance for biodiversity in these countries.

### 4.1 | Study significance and limitations

The higher exposure of KBAs compared with the rest of the study zone can be partly explained by their lower artificialness index and by the positive correlation between elevation and exposure metrics, as KBAs were located at higher elevations on average. For RC, this correlation could be due to its overestimation in areas with heterogeneous topography, resulting from the coarse spatial resolution (Garcia et al., 2014; Heikkinen et al., 2020) of the LUH2 dataset (Hurtt et al., 2020). However, the magnitude of RC and its higher values at high elevation are consistent with literature (e.g., Carroll et al., 2015; Hamann et al., 2015). Interpreting RC must also be done with great caution as it could be appealing to consider this metric as the pace required for organisms to track the same climatic conditions. Indeed, climate velocity does not account for dispersal capacity, nor for the different conditions that must be crossed (i.e., climate, habitat, and land-use) and might thus underestimate the speed of species dispersal required to track climatic conditions (Carroll et al., 2015; Parks et al., 2020). In our study, this is especially true in North Africa, as the Mediterranean Sea is a major constraint to the dispersion of many terrestrial species.

Spatial patterns of KBAs exposure were very different between the two climate change metrics (LC and RC), in line with Garcia et al. (2014), and between land-use and climate change exposure metrics. Although these findings may seem rather straightforward, we believe that they have important implications for biodiversity conservation. They suggest a limited overlap of KBAs highly exposed to climate change with KBAs highly exposed to land-use modifications. They thus emphasize the importance of using future projections of both land-use and climate when assessing the future impacts of global change on biodiversity (de Chazal & Rounsevell, 2009; Harfoot et al., 2014; Titeux et al., 2016), and also highlight the importance of accounting for both local and regional metrics. However, it is important to bear in mind that exposure metrics were given equal weight in the calculation of exposure indices (i.e., LEI, REI, and EI) although the environmental changes they describe might not all have the same level of impact on biodiversity.

As expected, but not yet shown with these scenarios, the exposure of KBAs to climate change increased with the radiative forcing level, reinforcing the necessity to dramatically reduce our greenhouse gas emissions.



**FIGURE 5** Exposure index of non-protected Key Biodiversity Area (KBA) cells (x-axis) and difference of exposure index between non-protected KBA cells and protected KBA cells (y-axis), averaged by country under each scenario. The bubble size represents the number of non-protected KBA cells and the color represents the proportion of non-protected KBA cells. Countries without protected KBA cells (Bosnia and Herzegovina, Egypt, Lebanon, and Tunisia) were assigned a value of 0 for the difference of exposure index between non-protected KBA cells and protected KBA cells. Countries with only protected KBA cells (Cyprus and Israel) were not displayed.

## 4.2 | Implications for spatial prioritization

KBAs are defined as sites of importance for biodiversity that must be targeted with conservation measures (Eken et al., 2004; IUCN, 2016; Margules & Pressey, 2000). Their higher exposure to climate change and land-use modifications than the rest of the study zone reinforces the necessity to implement conservation measures in KBAs of the Mediterranean region. If we follow a reactive approach of conservation planning, that is, if we allocate conservation measures in priority to highly vulnerable sites of importance for biodiversity (Brooks et al., 2006), KBAs that might face a very high level of threat in the next decades should be given particular priority. In contrast, proactive approaches of conservation planning, that is, approaches that prioritize sites of importance for biodiversity with low vulnerability (Brooks et al., 2006), would prioritize the less exposed KBAs, such as those located in Spain, North Macedonia, Portugal, and Bulgaria.

Whether we opt for a proactive or a reactive approach, the similarities in spatial patterns of exposure between future scenarios suggest that an appropriate allocation of conservation resources according to one scenario would still be appropriate in other scenarios, regardless of the socio-economic and climatic evolution of our society. Given that conservation resources are too often inadequate to ensure effective conservation measures (Coad et al., 2019), the robustness of this pattern across scenarios provides confidence to conservationists in selecting sites to prioritize. We believe that this is another incentive to implement conservation actions in Mediterranean KBAs.

Protected KBAs were more exposed than non-protected KBAs in two scenarios (SSP1-2.6 and SSP5-8.5). Nevertheless, many non-protected KBAs were highly exposed, probably because of the small number of protected KBAs compared to the number of non-protected KBAs. Furthermore, non-protected KBAs that were most exposed to climate change and land-use modifications (either in absolute terms or in comparison with protected

KBAs) were located in countries where KBAs are least integrated into the PAs network (either in number or in proportion). PAs are site-based conservation measures that can mitigate the effects of climate change (Thomas & Gillingham, 2015) and reduce natural habitat loss (Geldmann et al., 2013; Leberger et al., 2020). Therefore, we suggest adopting a reactive approach to make the most of the effectiveness of PAs in lessening the impacts of anthropogenic pressures, although we acknowledge that protection measures may not always be sufficient to reduce anthropogenic pressures to an appropriate level to accommodate important biodiversity. This reinforces the call for the designation of new PAs in KBAs of the Mediterranean region and especially in Middle-East and Maghreb countries. This conservation measure is all the more important and timely as KBAs are still insufficiently protected (Butchart et al., 2012; CBD, 2010; UNEP-WCMC & IUCN, 2021), new targets of land protection are about to be set and will urge countries to expand their PAs networks for 2030 (CBD, 2020), and Mediterranean biodiversity is very sensitive to land-use modifications and climate change (Newbold et al., 2020).

However, local and regional exposure metrics not only can be interpreted differently (Garcia et al., 2014), but are also unlikely to be influenced in the same way by the designation of PAs in KBAs. Indeed, protecting KBAs could prevent local land-use modifications (LA) and, to a lesser extent, mitigate local climate change (LC) through the reduction of interactions with other threats for instance (Mantyka-pringle et al., 2012). In contrast, protecting KBAs would not reduce their regional exposure, as it would not shorten their distance to KBA refuges (and thus RC) nor affect the difference of artificialness between KBAs and KBA refuges (RA). Values of RA were also mostly negative, certainly due to the difference in elevation (and therefore artificialness index) between KBAs and KBA refuges. Although we believe that it is crucial to consider the four exposure metrics that were used in this study, more importance should be given to local exposure metrics when identifying countries where the protection of KBAs should be strengthened.

Although it is crucial to anticipate the relocation of current climatic conditions of KBAs, we believe that using this study to designate PAs in current KBAs would be more effective and less hazardous than designating PAs in sites that are expected to have future climatic conditions analog to current KBAs (i.e., KBA refuges, Heller & Zavaleta, 2009). Indeed, protecting KBA refuges would not reduce the values of local exposure metrics (LC and LA) as they are computed only from KBA cells (Figure 2). Although it could assist the colonization of some species (Lehikoinen et al., 2019; Thomas

et al., 2012), protecting KBA refuges would also not shorten their distance to KBAs (and therefore RC). Finally, the future location of current climatic conditions of KBAs strongly differs between scenarios but also between GCMs, and communities may never reach the KBA refuge if it is too distant from the KBA. We thus recommend that new PAs be designated in highly exposed non-protected KBAs first and foremost.

### 4.3 | Perspectives

We believe that this original framework could be applied elsewhere to other networks of sites of importance for biodiversity to help prioritizing sites for the implementation of conservation measures such as the designation of new PAs or other land protection strategies. Other Effective area-based Conservation Measures (OECMs, IUCN-WCPA Task Force on OECMs, 2019), for instance, might offer an alternative to the designation of new PAs in KBAs (Donald et al., 2019). However, although this unprecedentedly comprehensive exposure assessment can help identify Mediterranean countries where to designate new PAs, it has limited applications to in-country identification of KBA sites to protect because of its spatial resolution. This study should therefore be complemented with additional analyses both at finer scale and accounting for other parameters (e.g., topography, land-cover, edaphic conditions, Carroll et al., 2017) to support the designation of new PAs in countries identified here as priority.

Reactive approaches of conservation planning prioritize highly vulnerable sites of importance for biodiversity for the allocation of conservation measures (Brooks et al., 2006). Assessing the other dimensions of the vulnerability of organisms currently inhabiting KBAs, that is, their sensitivity and adaptive capacity (IPCC, 2007), and combining them with their exposure using a trait-based vulnerability assessment (Pacifi et al., 2015) would thus complement this study. It would also be interesting to assess the vulnerability of species inhabiting KBAs using a correlative vulnerability assessment (Pacifi et al., 2015), for example, with species distributions models, and compare the results of the two approaches. The latter approach would further enable for an alternative identification of potential KBA refuges and provide the foundation for designating new PAs in sites that are projected to be of importance for some species in the Mediterranean region (Araújo et al., 2004).

PAs contribute to biodiversity conservation but also provide substantial social and economic benefits (Watson et al., 2014) as nature supplies multiple ecosystem services, for example, food provision, water filtration, air

purification, carbon storage, recreation, and resilience to extreme weather events. In Maghreb and Middle-East countries, where economic constraints hamper adequate financial support to PAs, quantifying these benefits could help convince governments to increase funding for KBAs protection (Emerton et al., 2006; Watson et al., 2014). Non-conventional and innovative financial sources and mechanisms, such as private and community funds (e.g., NGOs, philanthropic foundations, and businesses), development of nature sustainable tourism and involvement of local communities in the management of their natural heritage should also be further explored to ensure sufficient and sustainable funding of PAs as well as their long-term acceptance (Dharmaratne et al., 2000; Emerton et al., 2006; Watson et al., 2014). In addition, European countries should allocate a larger share of their international development assistance to biodiversity conservation. Finally, governments should be urged to honor the commitments to designate PAs they made by ratifying international conventions, for example, the identification of sites of international importance for waterbirds through the Ramsar Convention (Popoff et al., 2021).

#### AUTHOR CONTRIBUTIONS

**Fabien Verniest:** Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Resources, Writing—Original Draft, Writing—Review and Editing, Visualization. **Thomas Galewski:** Conceptualization, Writing—Review and Editing, Supervision, Project administration, Funding acquisition. **Romain Julliard:** Conceptualization, Writing—Review and Editing, Supervision, Project administration. **Anis Guelmami:** Resources, Data Curation, Writing—Review and Editing. **Isabelle Le Viol:** Conceptualization, Writing—Review and Editing, Supervision, Project administration, Funding acquisition.

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#### CONFLICT OF INTEREST

The authors declare that there is no potential conflict of interest to report.

#### DATA AVAILABILITY STATEMENT

Climate, land-use, and Key Biodiversity Areas data used for the analyses are publicly available through the websites and other sources listed in the Methods section. All scripts and exposure data are available upon request to Fabien Verniest.

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#### REFERENCES

- Angermeier, P. L. (2000). The natural imperative for biological conservation. *Conservation Biology*, 14, 373–381. <https://doi.org/10.1046/j.1523-1739.2000.98362.x>
- Araújo, M. B., Cabeza, M., Thuiller, W., Hannah, L., & Williams, P. H. (2004). Would climate change drive species out of reserves? An assessment of existing reserve-selection methods. *Global Change Biology*, 10(9), 1618–1626. <https://doi.org/10.1111/j.1365-2486.2004.00828.x>
- Batlloori, E., Parisien, M.-A., Parks, S. A., Moritz, M. A., & Miller, C. (2017). Potential relocation of climatic environments suggests high rates of climate displacement within the North American protection network. *Global Change Biology*, 23(8), 3219–3230. <https://doi.org/10.1111/gcb.13663>
- BirdLife International. (2014). *Important bird and biodiversity areas: A global network for conserving nature and benefiting people*. BirdLife International.
- BirdLife International. (2020). World database of key biodiversity areas. Developed by the KBA Partnership: BirdLife International, International Union for the Conservation of Nature, Amphibian Survival Alliance, Conservation International, Critical Ecosystem Partnership Fund, Global Environment Facility, Global Wildlife Conservation, NatureServe, Rainforest Trust, Royal Society for the Protection of Birds, Wildlife Conservation Society and World Wildlife Fund. [www.keybiodiversityareas.org](http://www.keybiodiversityareas.org). [Accessed 08/04/2020].
- Brooks, T. M., Mittermeier, R. A., da Fonseca, G. A. B., Gerlach, J., Hoffmann, M., Lamoreux, J. F., Mittermeier, C. G., Pilgrim, J. D., & Rodrigues, A. S. L. (2006). Global biodiversity conservation priorities. *Science*, 313, 58–61. <https://doi.org/10.1126/science.1127609>
- Butchart, S. H. M., Scharlemann, J. P. W., Evans, M. I., Quader, S., Aricò, S., Arinaitwe, J., Balman, M., Bennun, L. A., Bertzky, B.,

- Besançon, C., Boucher, T. M., Brooks, T. M., Burfield, I. J., Burgess, N. D., Chan, S., Clay, R. P., Crosby, M. J., Davidson, N. C., De Silva, N., ... Woodley, S. (2012). Protecting important sites for biodiversity contributes to meeting global conservation targets. *PLoS One*, *7*(3), e32529. <https://doi.org/10.1371/journal.pone.0032529>
- Carroll, C., Lawler, J. J., Roberts, D. R., & Hamann, A. (2015). Biotic and climatic velocity identify contrasting areas of vulnerability to climate change. *PLoS One*, *10*(10), e0140486. <https://doi.org/10.1371/journal.pone.0140486>
- Carroll, C., Roberts, D. R., Michalak, J. L., Lawler, J. J., Nielsen, S. E., Stralberg, D., Hamann, A., Mcrae, B. H., & Wang, T. (2017). Scale-dependent complementarity of climatic velocity and environmental diversity for identifying priority areas for conservation under climate change. *Global Change Biology*, *23*(11), 4508–4520. <https://doi.org/10.1111/gcb.13679>
- CBD (2010). COP 10 Decision X/2. Strategic plan for biodiversity 2011–2020. <http://www.cbd.int/decision/cop/?id=12268>.
- CBD (2020). Update of the zero draft of the post-2020 global biodiversity framework. CBD/POST2020/PREP/2/1.
- CEPF (2017). Mediterranean basin biodiversity hotspot—Ecosystem profile. Critical Ecosystem Partnership Fund.
- Coad, L., Watson, J. E. M., Geldmann, J., Burgess, N. D., Leverington, F., Hockings, M., Knights, K., & Di Marco, M. (2019). Widespread shortfalls in protected area resourcing undermine efforts to conserve biodiversity. *Frontiers in Ecology and the Environment*, *17*(5), 259–264. <https://doi.org/10.1002/fee.2042>
- Coetzee, B. W. T., Gaston, K. J., & Chown, S. L. (2014). Local scale comparisons of biodiversity as a test for global protected area ecological performance: A meta-analysis. *PLoS One*, *9*(8), e105824. <https://doi.org/10.1371/journal.pone.0105824>
- D'Amen, M., Bombi, P., Pearman, P. B., Schmatz, D. R., Zimmermann, N. E., & Bologna, M. A. (2011). Will climate change reduce the efficacy of protected areas for amphibian conservation in Italy? *Biological Conservation*, *144*(3), 989–997. <https://doi.org/10.1016/j.biocon.2010.11.004>
- Dawson, T. P., Jackson, S. T., House, J. I., Prentice, I. C., & Mace, G. M. (2011). Beyond predictions: Biodiversity conservation in a changing climate. *Science*, *332*, 53–58. <https://doi.org/10.1126/science.1200303>
- de Chazal, J., & Rounsevell, M. D. A. (2009). Land-use and climate change within assessments of biodiversity change: A review. *Global Environmental Change*, *19*(2), 306–315. <https://doi.org/10.1016/j.gloenvcha.2008.09.007>
- Dharmaratne, G. S., Yee Sang, F., & Walling, L. J. (2000). Tourism potentials for financing protected areas. *Annals of Tourism Research*, *27*, 590–610. [https://doi.org/10.1016/S0160-7383\(99\)00109-7](https://doi.org/10.1016/S0160-7383(99)00109-7)
- Donald, P. F., Buchanan, G. M., Balmford, A., Bingham, H., Couturier, A. R., de la Rosa, G. E., Gacheru, P., Herzog, S. K., Jathar, G., Kingston, N., Marnewick, D., Maurer, G., Reaney, L., Shmygaleva, T., Sklyarenko, S., Stevens, C. M. D., & Butchart, S. H. M. (2019). The prevalence, characteristics and effectiveness of aichi target 11's "other effective area-based conservation measures" (OECMs) in key biodiversity areas. *Conservation Letters*, *12*(5), e12659. <https://doi.org/10.1111/conl.12659>
- Dray, S., & Dufour, A.-B. (2007). The ade4 package: Implementing the duality diagram for ecologists. *Journal of Statistical Software*, *22*(4), 1–20. <https://doi.org/10.18637/jss.v022.i04>
- Drobinski, P., Da Silva, N., Bastin, S., Mailler, S., Muller, C., Ahrens, B., Christensen, O. B., & Lionello, P. (2020). How warmer and drier will the Mediterranean region be at the end of the twenty-first century? *Regional Environmental Change*, *20*, 78. <https://doi.org/10.1007/s10113-020-01659-w>
- Dudley, N. (Ed.). (2008). *Guidelines for applying protected area management categories*. IUCN x + 86pp. With Stolton, S., Shadie, P., and Dudley, N. (2013). IUCN WCPA Best Practice Guidance on Recognising Protected Areas and Assigning Management Categories and Governance Types, Best Practice Protected Area Guidelines Series No. 21. IUCN. xxpp.
- Eken, G., Bennun, L., Brooks, T. M., Darwall, W., Fishpool, L. D. C., Foster, M., Knox, D., Langhammer, P., Matiku, P., Radford, E., Salaman, P., Sechrest, W., Smith, M. L., Spector, S., & Tordoff, A. (2004). Key biodiversity areas as site conservation targets. *Bioscience*, *54*(12), 1110–1118. [https://doi.org/10.1641/0006-3568\(2004\)054\[1110:KBAASC\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2004)054[1110:KBAASC]2.0.CO;2)
- Emerton, L., Bishop, J., & Thomas, L. (2006). Sustainable financing of protected areas: a global review of challenges and options. In *Best practice protected area guidelines series*. IUCN.
- Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E. (2016). Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization. *Geoscientific Model Development*, *9*(5), 1937–1958. <https://doi.org/10.5194/gmd-9-1937-2016>
- Farr, T. G., Rosen, P. A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., & Alsdorf, D. (2007). The shuttle radar topography mission. *Reviews of Geophysics*, *45*, RG2004. <https://doi.org/10.1029/2005RG000183>
- Fick, S. E., & Hijmans, R. J. (2017). WorldClim 2: New 1-km spatial resolution climate surfaces for global land areas. *International Journal of Climatology*, *37*, 4302–4315. <https://doi.org/10.1002/joc.5086>
- Garcia, R. A., Cabeza, M., Rahbek, C., & Araújo, M. B. (2014). Multiple dimensions of climate change and their implications for biodiversity. *Science*, *344*(6183), 1247579. <https://doi.org/10.1126/science.1247579>
- Gaston, K. J. (2000). Global patterns in biodiversity. *Nature*, *405*, 220–227. <https://doi.org/10.1038/35012228>
- Geldmann, J., Barnes, M., Coad, L., Craigie, I. D., Hockings, M., & Burgess, N. D. (2013). Effectiveness of terrestrial protected areas in reducing habitat loss and population declines. *Biological Conservation*, *161*, 230–238. <https://doi.org/10.1016/j.biocon.2013.02.018>
- Gray, C. L., Hill, S. L. L., Newbold, T., Hudson, L. N., Börger, L., Contu, S., Hoskins, A. J., Ferrier, S., Purvis, A., & Scharlemann, J. P. W. (2016). Local biodiversity is higher inside than outside terrestrial protected areas worldwide. *Nature Communications*, *7*, 12306. <https://doi.org/10.1038/ncomms12306>
- Hamann, A., Roberts, D. R., Barber, Q. E., Carroll, C., & Nielsen, S. E. (2015). Velocity of climate change algorithms for guiding conservation and management. *Global Change Biology*, *21*(2), 997–1004. <https://doi.org/10.1111/gcb.12736>
- Harfoot, M., Tittensor, D. P., Newbold, T., McInerney, G., Smith, M. J., & Scharlemann, J. P. W. (2014). Integrated assessment models for ecologists: The present and the future. *Global Ecology and Biogeography*, *23*, 124–143. <https://doi.org/10.1111/geb.12100>

- Heikkinen, R. K., Leikola, N., Aalto, J., Aapala, K., Kuusela, S., Luoto, M., & Virkkala, R. (2020). Fine-grained climate velocities reveal vulnerability of protected areas to climate change. *Scientific Reports*, *10*, 1678. <https://doi.org/10.1038/s41598-020-58638-8>
- Heller, N. E., & Zavaleta, E. S. (2009). Biodiversity management in the face of climate change: A review of 22 years of recommendations. *Biological Conservation*, *142*(1), 14–32. <https://doi.org/10.1016/j.biocon.2008.10.006>
- Hijmans, R. J. (2019). geosphere: Spherical Trigonometry. R Package Version 1.5-10. <https://CRAN.R-project.org/package=geosphere>
- Hoffmann, S., Irl, S. D. H., & Beierkuhnlein, C. (2019). Predicted climate shifts within terrestrial protected areas worldwide. *Nature Communications*, *10*, 4787. <https://doi.org/10.1038/s41467-019-12603-w>
- Holman, I. P., Brown, C., Janes, V., & Sandars, D. (2017). Can we be certain about future land use change in Europe? A multi-scenario, integrated-assessment analysis. *Agricultural Systems*, *151*, 126–135. <https://doi.org/10.1016/j.agsy.2016.12.001>
- Hurt, G. C., Chini, L., Sahajpal, R., Frothingham, S., Bodirsky, B. L., Calvin, K., Doelman, J. C., Fisk, J., Fujimori, S., Klein Goldewijk, K., Hasegawa, T., Havlik, P., Heinemann, A., Humenberger, F., Jungclaus, J., Kaplan, J. O., Kennedy, J., Krutzin, T., Lawrence, D., ... Zhang, X. (2020). Harmonization of global land use change and management for the period 850–2100 (LUH2) for CMIP6. *Geoscientific Model Development*, *13*(11), 5425–5464. <https://doi.org/10.5194/gmd-13-5425-2020>
- IPBES (2016). The methodological assessment report on scenarios and models of biodiversity and ecosystem services. In S. Ferrier, K. N. Ninan, P. Leadley, R. Alkemade, L. A. Acosta, H. R. Akçakaya, L. Brotons, W. W. L. Cheung, V. Christensen, K. A. Harhash, J. Kabubo-Mariara, C. Lundquist, M. Obersteiner, H. M. Pereira, G. Peterson, R. Pichs-Madruga, N. Ravindranath, C. Rondinini, & B. A. Wintle (Eds.), *Secretariat of the intergovernmental science-policy platform on biodiversity and ecosystem services* (p. 348). IPBES.
- IPBES (2019). Summary for policymakers of the global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. In S. Díaz, J. Settele, E. S. Brondízio, H. T. Ngo, M. Guèze, J. Agard, A. Arneth, P. Balvanera, K. A. Brauman, S. H. M. Butchart, K. M. A. Chan, L. A. Garibaldi, K. Ichii, J. Liu, S. M. Subramanian, G. F. Midgley, P. Miloslavich, Z. Molnár, D. Obura, ...C. N. Zayas (Eds.), (56 pp.) IPBES secretariat.
- IPCC (2007). Climate Change 2007: Impacts, adaptation and vulnerability. M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, & C. E. Hanson (Eds.), *Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change* (976 pp.). Cambridge University Press.
- IPCC (2021). Climate change 2021: The physical science basis. V. Masson-Delmotte, P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, & B. Zhou (Eds.), *Contribution of working group I to the sixth assessment report of the intergovernmental panel on climate change*. In Press.
- IUCN (Ed.). (2016). *A global standard for the identification of key biodiversity areas, Version 1.0* (1st ed.). IUCN.
- IUCN-WCPA Task Force on OECMs. (2019). *Recognising and reporting other effective area-based conservation measures*. IUCN.
- Joppa, L. N., & Pfaff, A. (2009). High and far: Biases in the location of protected areas. *PLoS One*, *4*(12), e8273. <https://doi.org/10.1371/journal.pone.0008273>
- Kendall, M. G. (1948). *Rank correlation methods*. Griffin.
- Lapola, D. M., Silva, J. M. C. d., Braga, D. R., Carpijani, L., Ogawa, F., Torres, R. R., Barbosa, L. C. F., Ometto, J. P. H. B., & Joly, C. A. (2020). A climate-change vulnerability and adaptation assessment for Brazil's protected areas. *Conservation Biology*, *34*, 427–437. <https://doi.org/10.1111/cobi.13405>
- Leberger, R., Geizendorffer, I. R., Gaget, E., Gwelami, A., Galewski, T., Pereira, H. M., & Guerra, C. A. (2020). Mediterranean wetland conservation in the context of climate and land cover change. *Regional Environmental Change*, *20*, 67. <https://doi.org/10.1007/s10113-020-01655-0>
- Lehikoinen, P., Santangeli, A., Jaatinen, K., Rajasärkkä, A., & Lehikoinen, A. (2019). Protected areas act as a buffer against detrimental effects of climate change—Evidence from large-scale, long-term abundance data. *Global Change Biology*, *25*(1), 304–313. <https://doi.org/10.1111/gcb.14461>
- Machado, A. (2004). An index of naturalness. *Journal for Nature Conservation*, *12*(2), 95–110. <https://doi.org/10.1016/j.jnc.2003.12.002>
- Malek, Ž., Verburg, P. H., Geizendorffer, I. R., Bondeau, A., & Cramer, W. (2018). Global change effects on land management in the Mediterranean region. *Global Environmental Change*, *50*, 238–254. <https://doi.org/10.1016/j.gloenvcha.2018.04.007>
- Mantyka-pringle, C. S., Martin, T. G., & Rhodes, J. R. (2012). Interactions between climate and habitat loss effects on biodiversity: A systematic review and meta-analysis. *Global Change Biology*, *18*(4), 1239–1252. <https://doi.org/10.1111/j.1365-2486.2011.02593.x>
- Margules, C. R., & Pressey, R. L. (2000). Systematic conservation planning. *Nature*, *405*, 243–253. <https://doi.org/10.1038/35012251>
- MedECC (2020). Climate and environmental change in the Mediterranean basin—Current situation and risks for the future. In W. Cramer, J. Guiot, K. Marini (Eds.), *First Mediterranean assessment report* (632 pp). Union for the Mediterranean, Plan Bleu, UNEP/MAP.
- Millennium Ecosystem Assessment. (2005). *Ecosystems and human well-being: Biodiversity synthesis*. World Resources Institute.
- Myers, N., Mittermeier, R. A., Mittermeier, C. G., da Fonseca, G. A. B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. *Nature*, *403*, 853–858. <https://doi.org/10.1038/35002501>
- Newbold, T. (2018). Future effects of climate and land-use change on terrestrial vertebrate community diversity under different scenarios. *Proceedings of the Royal Society B: Biological Sciences*, *285*(1881), 20180792. <https://doi.org/10.1098/rspb.2018.0792>
- Newbold, T., Hudson, L. N., Hill, S. L. L., Contu, S., Lysenko, I., Senior, R. A., Börger, L., Bennett, D. J., Choimes, A., Collen, B., Day, J., De Palma, A., Díaz, S., Echeverria-Londoño, S., Edgar, M. J., Feldman, A., Garon, M., Harrison, M. L. K., Alhousseini, T., ... Purvis, A. (2015). Global effects of land use on local terrestrial biodiversity. *Nature*, *520*, 45–50. <https://doi.org/10.1038/nature14324>



- Newbold, T., Oppenheimer, P., Etard, A., & Williams, J. J. (2020). Tropical and Mediterranean biodiversity is disproportionately sensitive to land-use and climate change. *Nature Ecology & Evolution*, 4, 1630–1638. <https://doi.org/10.1038/s41559-020-01303-0>
- O'Neill, B. C., Kriegler, E., Riahi, K., Ebi, K. L., Hallegatte, S., Carter, T. R., Mathur, R., & van Vuuren, D. P. (2014). A new scenario framework for climate change research: The concept of shared socioeconomic pathways. *Climatic Change*, 122, 387–400. <https://doi.org/10.1007/s10584-013-0905-2>
- O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G. C., Knutti, R., Kriegler, E., Lamarque, J.-F., Lowe, J., Meehl, G. A., Moss, R., Riahi, K., & Sanderson, B. M. (2016). The scenario model intercomparison project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, 9(9), 3461–3482. <https://doi.org/10.5194/gmd-9-3461-2016>
- Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Loucks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P., & Kassem, K. R. (2001). Terrestrial ecoregions of the world: A new map of life on Earth. *Bioscience*, 51(11), 933–938. [https://doi.org/10.1641/0006-3568\(2001\)051\[0933:TEOTWA\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2)
- Pacifici, M., Foden, W. B., Visconti, P., Watson, J. E. M., Butchart, S. H. M., Kovacs, K. M., Scheffers, B. R., Hole, D. G., Martin, T. G., Akçakaya, H. R., Corlett, R. T., Huntley, B., Bickford, D., Carr, J. A., Hoffmann, A. A., Midgley, G. F., Pearce-Kelly, P., Pearson, R. G., Williams, S. E., ... Rondinini, C. (2015). Assessing species vulnerability to climate change. *Nature Climate Change*, 5, 215–224. <https://doi.org/10.1038/nclimate2448>
- Parks, S. A., Carroll, C., Dobrowski, S. Z., & Allred, B. W. (2020). Human land uses reduce climate connectivity across North America. *Global Change Biology*, 26(5), 2944–2955. <https://doi.org/10.1111/gcb.15009>
- Popoff, N., Gaget, E., Béchet, A., Dami, L., du Rau, P. D., Geijzendorffer, I., Guelmami, A., Mondain-Monval, J.-Y., Perennou, C., Suet, M., Verniest, F., Deschamps, C., Taylor, N. G., Azafzaf, H., Bendjedda, N., Bino, T., Borg, J. J., Božič, L., Dakki, M., ... Galewski, T. (2021). Gap analysis of the Ramsar site network at 50: over 150 important Mediterranean sites for wintering waterbirds omitted. *Biodiversity and Conservation*, 30(11), 3067–3085. <https://doi.org/10.1007/s10531-021-02236-1>
- QGIS Development Team (2020). *QGIS Geographic Information System. Open Source Geospatial Foundation Project*. <http://qgis.osgeo.org>
- R Core Team. (2019). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing <https://www.R-project.org/>
- Ricketts, T. H., Dinerstein, E., Boucher, T., Brooks, T. M., Butchart, S. H. M., Hoffmann, M., Lamoreux, J. F., Morrison, J., Parr, M., Pilgrim, J. D., Rodrigues, A. S. L., Sechrest, W., Wallace, G. E., Berlin, K., Bielby, J., Burgess, N. D., Church, D. R., Cox, N., Knox, D., ... Wikramanayake, E. (2005). Pinpointing and preventing imminent extinctions. *Proceedings of the National Academy of Sciences*, 102(51), 18497–18501. <https://doi.org/10.1073/pnas.0509060102>
- Rodrigues, A. S. L., & Cazalis, V. (2020). The multifaceted challenge of evaluating protected area effectiveness. *Nature Communications*, 11, 5147. <https://doi.org/10.1038/s41467-020-18989-2>
- Sala, O. E. (2000). Global biodiversity scenarios for the year 2100. *Science*, 287, 1770–1774. <https://doi.org/10.1126/science.287.5459.1770>
- Sanderson, E. W., Jaiteh, M., Levy, M. A., Redford, K. H., Wannebo, A. V., & Woolmer, G. (2002). The human footprint and the last of the wild. *Bioscience*, 52(10), 891–904. [https://doi.org/10.1641/0006-3568\(2002\)052\[0891:THFATL\]2.0.CO;2](https://doi.org/10.1641/0006-3568(2002)052[0891:THFATL]2.0.CO;2)
- Santos, M. J., Smith, A. B., Dekker, S. C., Eppinga, M. B., Leitão, P. J., Moreno-Mateos, D., Morueta-Holme, N., & Ruggeri, M. (2021). The role of land use and land cover change in climate change vulnerability assessments of biodiversity: A systematic review. *Landscape Ecology*, 36, 3367–3382. <https://doi.org/10.1007/s10980-021-01276-w>
- Scriven, S. A., Hodgson, J. A., McClean, C. J., & Hill, J. K. (2015). Protected areas in Borneo may fail to conserve tropical forest biodiversity under climate change. *Biological Conservation*, 184, 414–423. <https://doi.org/10.1016/j.biocon.2015.02.018>
- Stokstad, E. (2020). Global efforts to protect biodiversity fall short. *Science*, 369, 1418. <https://doi.org/10.1126/science.369.6510.1418>
- Thomas, C. D., & Gillingham, P. K. (2015). The performance of protected areas for biodiversity under climate change. *Biological Journal of the Linnean Society*, 115(3), 718–730. <https://doi.org/10.1111/bij.12510>
- Thomas, C. D., Gillingham, P. K., Bradbury, R. B., Roy, D. B., Anderson, B. J., Baxter, J. M., Bourn, N. A. D., Crick, H. Q. P., Findon, R. A., Fox, R., Hodgson, J. A., Holt, A. R., Morecroft, M. D., O'Hanlon, N. J., Oliver, T. H., Pearce-Higgins, J. W., Procter, D. A., Thomas, J. A., Walker, K. J., ... Hill, J. K. (2012). Protected areas facilitate species' range expansions. *Proceedings of the National Academy of Sciences*, 109(35), 14063–14068. <https://doi.org/10.1073/pnas.1210251109>
- Titeux, N., Henle, K., Mihoub, J.-B., Regos, A., Geijzendorffer, I. R., Cramer, W., Verburg, P. H., & Brotons, L. (2016). Biodiversity scenarios neglect future land-use changes. *Global Change Biology*, 22(7), 2505–2515. <https://doi.org/10.1111/gcb.13272>
- UNEP/MAP & Plan Bleu (2020). *State of the Environment and Development in the Mediterranean*. United Nations Environment Programme/Mediterranean Action Plan and Plan Bleu. Nairobi.
- UNEP-WCMC & IUCN (2021). *Protected Planet Live Report 2020*. UNEP-WCMC and IUCN.
- UNEP-WCMC & IUCN. (2020). *Protected planet: The world database on protected areas (WDPA), [December 2019 version]*. UNEP-WCMC and IUCN. [www.protectedplanet.net](http://www.protectedplanet.net)
- van Vuuren, D. P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G. C., Kram, T., Krey, V., Lamarque, J.-F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S. J., & Rose, S. K. (2011). The representative concentration pathways: An overview. *Climatic Change*, 109, 5–31. <https://doi.org/10.1007/s10584-011-0148-z>
- Venter, O., Magrath, A., Outram, N., Klein, C. J., Possingham, H. P., Di Marco, M., & Watson, J. E. M. (2018).

- Bias in protected-area location and its effects on long-term aspirations of biodiversity conventions. *Conservation Biology*, 32(1), 127–134. <https://doi.org/10.1111/cobi.12970>
- Watson, J. E. M., Dudley, N., Segan, D. B., & Hockings, M. (2014). The performance and potential of protected areas. *Nature*, 515, 67–73. <https://doi.org/10.1038/nature13947>
- Wilcoxon, F. (1992). Individual comparisons by ranking methods. In S. Kotz & N. L. Johnson (Eds.), *Breakthroughs in Statistics*. Springer Series in Statistics (Perspectives in Statistics). Springer. [https://doi.org/10.1007/978-1-4612-4380-9\\_16](https://doi.org/10.1007/978-1-4612-4380-9_16)
- Wilson, T. S., Sleeter, B. M., Sleeter, R. R., & Soulard, C. E. (2014). Land-use threats and protected areas: A scenario-based, landscape level approach. *Land*, 3, 362–389. <https://doi.org/10.3390/land3020362>

## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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