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Incorporating climate velocity into the design of climate-smart networks of marine protected areas

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Abstract

1. Climate change is redistributing terrestrial and marine biodiversity and altering fundamental ecological interactions. To conserve biodiversity and promote its long-term persistence, protected areas should account for the ecological implications of species' redistribution. Data paucity across many systems means that achieving this goal requires generic metrics that act as proxies for likely responses of multiple taxa to climate change. Climate velocity is one such metric, representing the potential speed and direction of species' range shifts.
2. Here, we explore three approaches for incorporating climate velocity into the design of marine protected areas and demonstrate their application in the Mediterranean Sea. Our methods are designed to meet the climate-smart adaptation strategy of protecting climate refugia by selecting slow-moving climate velocity areas.
3. For our case study, we found that incorporating climate velocity as a cost measure in Marxan best selects slower moving areas, which are robust indicators of climate refugia. However, this approach is unable to accommodate socio-economic cost data and is thus impractical. Incorporating climate velocity as a boundary or as a feature selects slower moving areas with a lower socio-economic cost. We recommend incorporating velocity as a boundary, where possible because it is a more flexible approach. The boundary approach considers the climate velocity of all planning units, rather than being limited to a subjective classification of 'slow-moving' planning units when treated as a feature. However, further assessment is required. For different planning scales and for grid structures other than squares, the relative performance of incorporating climate velocity as a boundary or as a feature might vary among case studies.

Nur Arafeh-Dalmau and Isaac Brito-Morales contributed equally to this work.

4. This work presents simple and practical ways of including climate velocity in conservation plans to achieve the key climate-smart objective of protecting climate refugia, thereby enhancing ecological resilience. Our methods are widely applicable, encouraging researchers and practitioners to advance the field and deliver networks of climate-smart protected areas by 2030.

KEYWORDS

climate adaptation, conservation planning, marine reserves, marine spatial planning, post-2020 conservation targets, spatial prioritization

1 | INTRODUCTION

Protected areas are an effective tool for protecting biodiversity and are a cornerstone of most conservation strategies (Edgar et al., 2014; Gray et al., 2016). Spatial conservation prioritization is among the most common approaches used to support the design of networks of protected areas that achieve conservation and socio-economic goals (Moilanen et al., 2009). However, although data on current and future ecological processes are critical when identifying protected areas, climate change and its impacts are rarely incorporated into spatial conservation prioritizations (Álvarez-Romero et al., 2018; Jones et al., 2016; Reside et al., 2018; Tittensor et al., 2019).

Although marine protected areas help species within their boundaries adapt to a changing climate (Duarte et al., 2020; Micheli et al., 2012; Roberts et al., 2017), species shift their biogeographic distributions to track their preferred thermal niches as climate changes (Pecl et al., 2017). In doing so, they potentially move across the boundaries of existing marine protected areas (Bates et al., 2019), altering fundamental ecological interactions and creating new ones (Pecl et al., 2017). Accounting for the movement of species in the design of marine protected areas will promote the long-term persistence of biodiversity (Fredston-Hermann et al., 2018).

Climate-smart conservation is a multiple-step approach that considers climate change adaptation (Hansen et al., 2010; Stein et al., 2014) when designing marine protected areas. Climate adaptation involves strategies to address species' and ecosystems' vulnerabilities to climate change while adopting goals based on future climatic and ecological conditions. Among other adaptation strategies (West et al., 2017; Wilson et al., 2020), climate-smart conservation prioritizes retention of habitats and species within protected areas under future climate scenarios (Lawler et al., 2020; Maxwell et al., 2019; Sala et al., 2021). Moreover, systems of marine protected areas that retain species within their boundaries should also better maintain the functioning of ecosystems (Fredston-Hermann et al., 2018; Nagelkerken et al., 2020), because species interactions experience least change when turnover of biodiversity is minimized (Burrows et al., 2014; Cahill et al., 2013; Molinos et al., 2016). Regions that retain their climates over long periods represent climate refugia and should therefore be prioritized for their protection (Keppel et al., 2015).

Climate-change adaptation strategies are usually incorporated into marine spatial plans by prioritizing 'future habitats' or 'representing climate refugia' identified by species distribution models projected into the future based on climate-change scenarios (Jones et al., 2016). Despite significant advances, prohibitive costs of collecting biotic data, especially from the ocean, result in data deficiencies that limit the development of predictive models for the majority of species (Sequeira et al., 2018). Moreover, there are questions about how transferable these models are across both space and time (Robinson et al., 2011; Yates et al., 2018). A potential solution is to use generic metrics, such as climate velocity, that describe likely responses of multiple taxa to climate change (Brito-Morales et al., 2018).

Climate velocity describes the speed and direction that a species at a given point in space would need to move to remain within its climatic niche (Loarie et al., 2009). This metric has been used to inform potential species distribution shifts, providing information about how biodiversity might be rearranged under a changing climate (Burrows et al., 2011; Hiddink et al., 2012; Molinos et al., 2016). The few examples that have used climate velocity in spatial prioritization have focused on identifying terrestrial climate refugia, and do not consider other important factors when designing protected areas (Carroll et al., 2017; Haight & Hammill, 2020; Stralberg et al., 2020). For example, Carroll et al. (2017) compared the performance of six approaches, including climate velocity, to identify priority refugia for protection, but did not represent biodiversity (at the species or habitat level) or incorporate socio-economic costs. Similarly, Haight and Hammill (2020) used climate velocity metrics as a cost in prioritizing the protection of climate refugia for a range of terrestrial species, but also overlooked socio-economic costs. Stralberg et al. (2020) considered multiple objectives for climate refugia, evaluated the contribution of each to the prioritization plan and used the Human Development Index as a cost layer, even though this is not a direct measure of socio-economic cost. To advance the inclusion of climate velocity into the framework for climate-smart marine protected areas, we need simple approaches that include current best-practice protected-area design principles, including adequate representation of biodiversity and minimizing socio-economic costs.

Currently, no practical advice exists on how to incorporate climate velocity metrics to meet the climate-smart adaptation strategy of protecting climate refugia at a community or broad biogeographic level (Fredston-Hermann et al., 2018). Given that maximizing species retention is also likely to minimize changes in species' interactions, and that the latter have been a cause of extirpations and population declines during previous periods of climate change (Cahill et al., 2013), prioritizing the protection of climate refugia, characterized by their slow climate velocity (Sandel et al., 2011), could contribute significantly to climate-smart conservation strategies.

Here, we assess several methods of incorporating climate velocity into the design of climate-smart systems of marine protected areas. Although we illustrate the methods using the Mediterranean Sea as a case study, the methods are equally applicable to terrestrial systems. We address the climate-smart adaptation strategy to protect climate refugia by maximizing the selection of areas of slow climate velocity. We evaluate the resulting marine protected-area networks in terms of their climate velocity and socio-economic cost. Our aim is not to suggest a network of marine protected areas that could be implemented in the Mediterranean Sea, but rather to develop, evaluate and compare approaches for incorporating climate velocity into the climate-smart protected area toolkit.

2 | MATERIALS AND METHODS

2.1 | Case study

The Mediterranean Sea is considered a climate change 'hotspot' (Cramer et al., 2018; Giorgi, 2006), warming two-to-three times faster than the ocean as a whole (Vargas-Yáñez et al., 2008), making it an ideal region to test our approach. This semi-enclosed basin is home to a high proportion of endemic species, some of which have limited abilities to track their preferred thermal conditions because of geographic obstructions (Burrows et al., 2014; Lejeusne et al., 2010). We divide this planning domain into 4,649 square planning units of 0.25° × 0.25° (coastal squares were smaller as they were clipped to the coastline). We used 0.25° grid square cells as our planning units shape because: (a) this is the finest resolution of global climate models, (b) coarser resolutions could be inappropriate for planning networks of marine protected areas and for meaningfully interpreting climate velocity in the ocean and (c) square planning units match the shape of grid cells in the climate models.

2.2 | Climate velocity

We calculated local climate velocity (after Burrows et al., 2011) for the period 2020–2100 using the VoCC R package (García Molinos et al., 2019) and sea surface temperature (SST) projections from the MPI-ESM1-2-HR model at 0.5° spatial resolution (Figure 1a–c). We used three climate scenarios generated under the IPCC Shared Socio-Economic Pathways (SSPs): SSP1-2.6, SSP2-4.5 and SSP5-8.5 (O'Neill et al., 2017). SSP1-2.6 represents an optimistic scenario with a peak in radiative forcing at ~3 W/m^2 by 2100. SSP2-4.5 reflects intermediate challenges for mitigation with radiative forcing stabilized at ~4.5 W/m^2 by 2100. SSP5-8.5 represents a reference climate scenario with a continued increase in greenhouse gas emissions with radiative forcing reaching >8.5 W/m^2 by 2100 and rising after that. We did not use multiple future models, as is commonly done for climate-change research (Harris et al., 2014; Lotze et al., 2019). This was because our aim here is not to provide a comprehensive assessment of climate-change risks in the region but to illustrate multiple approaches to incorporating climate velocity in the design of climate-smart marine protected areas and their relative strengths and weaknesses.

2.3 | Data for biodiversity features

We represented the biodiversity of our study region using AquaMaps data (Kaschner et al., 2019), which estimates the probability of occurrence (0–1) for each species at 0.5° spatial resolution derived from occurrence observations and environmental-niche models based on depth, temperature, salinity and oxygen. We used a threshold probability of 0.5 to compile range maps for our analysis, following the study by Klein et al. (2015); this can be adjusted to the specific biodiversity data used. Our approach yielded 1,471 species distribution maps for the planning domain (Figure 1d; Table S1). These were used as conservation features to estimate the spatial overlay of each species in each 0.25° planning unit. Although we used AquaMaps data, conservation practitioners could replace these with the best available information for the distribution of biodiversity in their study domain.

2.4 | Opportunity costs

We used a surrogate cost layer for the Mediterranean Sea from Mazor et al. (2014) that represents the combined spatial opportunity cost in monetary value (Euros) for commercial (small- and large-scale) fishing, non-commercial (recreational and subsistence) fishing and aquaculture activities (Figure 1e). Commercial fishing data are based on fish tonnage caught over 28 geographical regions provided by the General Fisheries Commission for the Mediterranean Sea and the average market value of species. Non-commercial fishing data are based on the number of recreational fishers per country, the cost of expenditure on fishing gear and the value of catch per year within 12-nautical-mile territorial waters. Aquaculture cost estimates are based on the production multiplied by the market value of the primary aquaculture species in the Mediterranean Sea. We aggregated the combined cost layer from 10 km^2 to 0.25° grid cells to match our planning unit size by summing the original cost values, weighted by the proportion of each original cell in each planning unit.

2.5 | Spatial prioritization approach

We used the spatial prioritization software Marxan to identify conservation priority areas for meeting the climate-smart adaptation

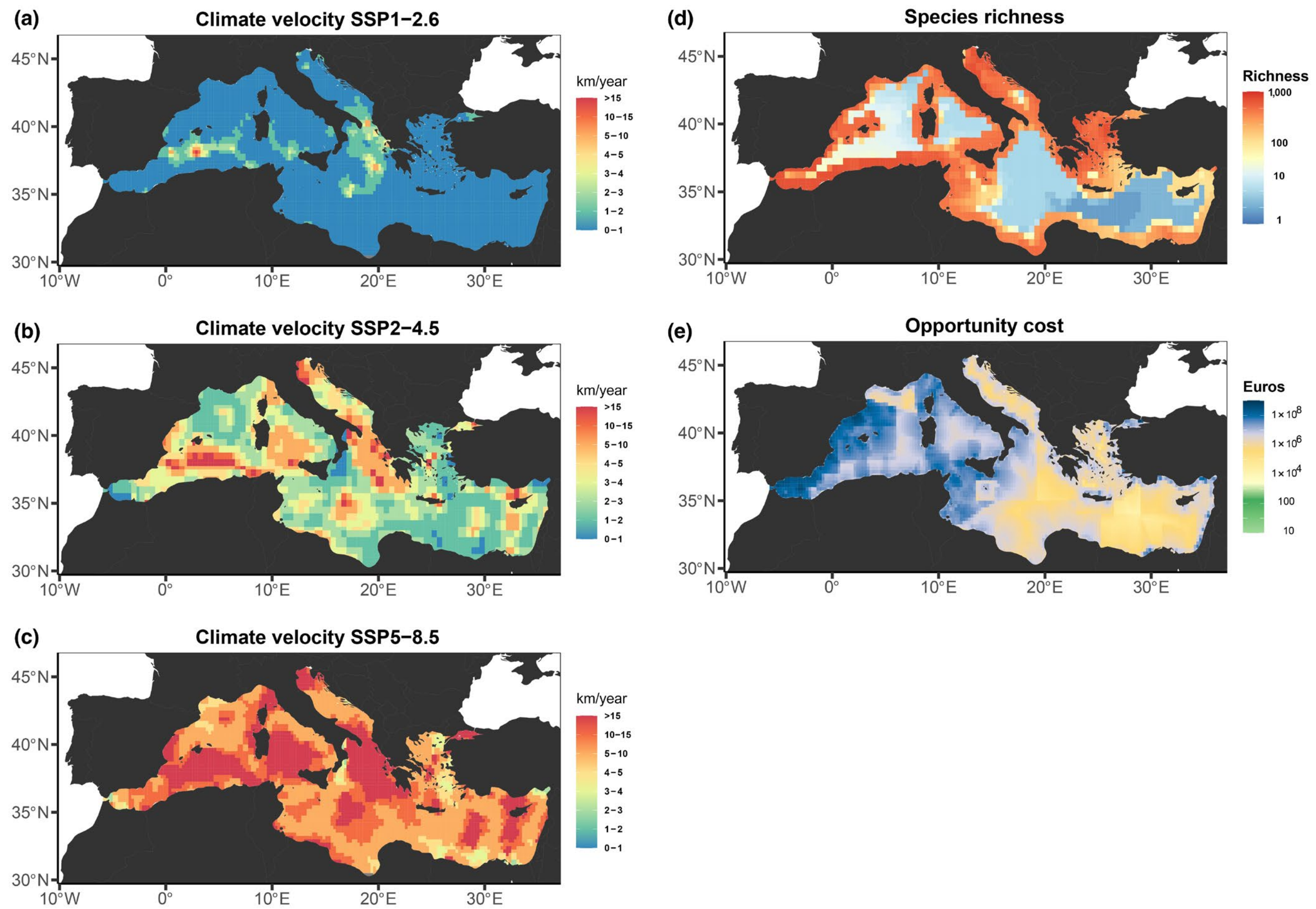

FIGURE 1 Maps of the study area quantifying the climate velocity for the MPI-ESM1-2-HR Earth-system model under (a) SSP1-2.6, (b) SSP2-4.5 and (c) SSP5-8.5; (d) species richness and (e) the opportunity cost (Euros)

strategy of protecting climate refugia (Table 1). Marxan uses the simulated annealing algorithm (Ball et al., 2009) to find near-optimal solutions that meet a set of quantitative conservation targets, while minimizing the total perimeter of the reserve system and its total 'cost'. While cost is always minimized for a given reserve size, flexibility in the compactness of the reserve network can be controlled by modifying the boundary length modifier parameter in Marxan. We used Marxan because it is the most commonly used spatial prioritization software for reserve planning, but our methods are applicable to other decision support tools.

2.6 | Planning scenarios

We constructed four planning scenarios that varied in their use and treatment of climate velocity and opportunity cost data (Table 1). All four planning scenarios aimed to represent 20% of each species' distribution for a minimum cost. We used uniform targets rather than varying targets across species (e.g. higher values for rare or vulnerable species) as our aim here is only to illustrate our method. Scenario 1—'Base'—did not attempt to meet any climate-smart adaptation strategy, but included the opportunity cost. In Scenarios 2–4, we prioritized climate refugia based on climate velocity. In Scenario 2—'Velocity as a Cost'—we followed Haight and Hammill (2020) by replacing the opportunity cost data with climate velocity as the cost layer (to minimize the selection of planning units with high climate velocities). In Scenario 3—'Velocity as a Boundary'—we replaced the perimeter of planning units with the magnitude of climate velocity and used this as a boundary length to prioritize the selection of slow-velocity planning units, while minimizing the opportunity cost (see next sections). Finally, in Scenario 4—'Velocity as a Feature'—we set a target of representing 25% of the slowest moving planning units (defined as the 25th percentile of climate velocities) after calibrating the representation target (see next section).

Because there is debate whether cost measures should include composites of variables in different units (e.g. in this case, the opportunity cost in Euros and climate velocity in km/decade), we did not explore an approach to incorporate climate velocity using a cost metric that combines opportunity cost and climate velocity as it is not recommended best practice (see Ban and Klein (2009) for a review on this topic).

For this study, we evaluated the strengths and weakness of each approach under one climate scenario: SSP2-4.5. However, to test whether different climate scenarios influence the general performance of each approach, we conducted a sensitivity analysis based on climate scenarios SSP1-2.6 and SSP5-8.5.

TABLE 1 Spatial prioritization approaches (planning scenarios) based on climate-smart adaptation strategies, opportunity cost and climate-change metrics

Scenario	Climate-smart adaptation strategy	Climate target	Climate velocity input	Approach	Cost layer
Base	None	No climate target	None	None	Fishing
Velocity as a Cost	Protect climate refugia	Selection of planning units with slow climate velocities	Climate velocity	Climate velocity as a cost measure	Climate
Velocity as a Boundary	Protect climate refugia	Selection of planning units with slow climate velocities	Climate velocity	Climate velocity as a boundary magnitude	Fishing
Velocity as a Feature	Protect climate refugia	Represent slow climate velocity areas	Climate velocity	Set a target for areas of slow climate velocities and treat them as conservation features	Fishing

For each planning scenario, we ran Marxan 100 times with 10 million iterations. We used a tailored approach to calibrate the number of iterations, the species penalty factor and the boundary length modifier (see Supporting Information, Figures S1 and S2; Figure 2; Table S2 and http://doi.org/10.5281/zenodo.3876041 for the code Brito-Morales and Arafeh-Dalmau, 2020a). When using Marxan, it is necessary to run a calibration analysis. The objective of the calibration is to select a suite of parameters for each scenario that trade-off minimizing the opportunity cost and selecting slow-moving areas. These are not planning scenarios, but calibration runs. Next, we calibrated the representation target assigned to the slowest moving planning units for the Velocity as a Feature scenario to find the optimal trade-off between cost, fragmentation and area of the solution (see Supporting Information, Figure 3). Finally, we also conducted a sensitivity analysis and varied the percentile threshold for slow-moving planning units (15th and 35th percentile) and the representation targets to assess whether different classifications influence the general performance of the Velocity as a Feature scenario (Figures S3 and S4).

2.7 | Climate Velocity as a Boundary

For the Velocity as a Boundary scenario, we developed an approach that modified the Marxan objective function to favour both the selection and the spatial aggregation of planning units with slow climate velocities. We assigned the magnitude of climate velocity in each planning unit as its boundary length. Where two planning units shared a boundary, we estimated the shared boundary length as the average of the magnitudes of climate velocities of the two cells. We could thus control the importance of climate velocity relative to the conservation targets and costs of the prioritization approach using the boundary length modifier. A zero value for the boundary length modifier means that there is no preference for selecting areas of slower or faster climate velocity, with an increasing value resulting in a greater emphasis on climate velocity in the selection of planning units to be included in the protected-area network. When applying non-zero values for the boundary length modifier, Marxan seeks to minimize the sum of the magnitudes of shared climate velocities. With these modifications, Marxan solves the conservation planning problem of minimizing the sum of the total cost of selected sites, as well as the sum of the averaged climate velocity magnitudes between shared boundaries across selected sites, subject to meeting the target for every biodiversity feature. Thus, a larger boundary length modifier value will favour the selection and aggregation of slower velocity areas (Figure 2).

2.8 | Comparing efficiency and spatial similarity among approaches

We evaluated the trade-offs among the different planning scenarios used to prioritize climate refugia (Scenarios 2–4) and the Base scenario by assessing their efficiency in minimizing the total opportunity cost and the median climate velocity of selected planning units from 100 spatially different solutions to the problem. We used nonparametric one-way analysis of ranks (Kruskal–Wallis H test), with subsequent pairwise post hoc comparisons (pairwise Wilcoxon tests, with Bonferroni correction for multiple tests), to examine differences among the planning scenarios for each climate scenario in terms of minimizing opportunity cost and selecting for slow-moving planning units.

We also evaluated the spatial similarity (overlap) of the selection frequencies of the planning units among different planning scenarios. The selection frequency, the number of times a planning unit was selected in the 100 solutions, is a good indicator of their irreplaceability (Stewart & Possingham, 2005), and is commonly used to identify priority areas for conservation. Following this logic, we compared solutions based on Cohen's kappa coefficient. This pairwise statistic (McHugh, 2012) indicates how much the selection frequencies of the planning units overlap among scenarios. Kappa ranges from −1 to +1, where −1 indicates complete disagreement, 0 indicates overlap due to chance and +1 indicates complete agreement (Landis & Koch, 1977). We followed the approach of (Ruiz-Frau et al., 2015) and classified planning unit selection frequency into five classes (0, <25%, 25%–50%, 50%–75% and >75%).

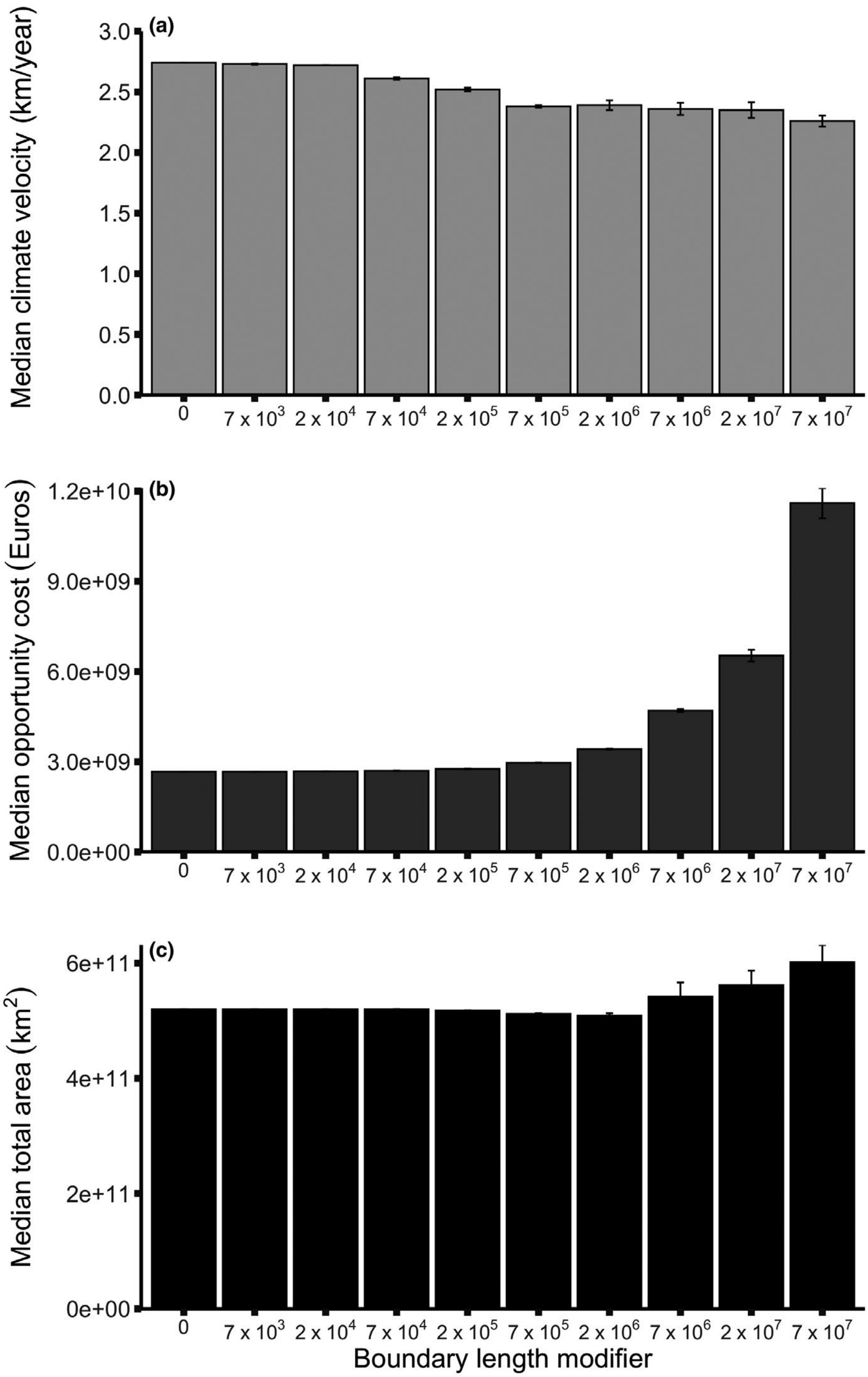

FIGURE 2 Calibration runs for Velocity as a Boundary scenario under SSP2-4.5. (a) Climate velocity, (b) opportunity cost in monetary value and (c) total area from 100 runs (± 95% nonparametric confidence intervals) generated in Marxan

3 | RESULTS

3.1 | Performance

The Kruskal–Wallis test revealed significant differences ($p \leq 2.2e^{-16}$) between the four planning scenarios for minimizing the opportunity cost and selecting slow-moving areas. Velocity as a Feature ranked the first for the opportunity cost, followed by the Base scenario and Velocity as a Boundary, while Velocity as a Cost ranked last (Table 2). On the other hand, Velocity as a Cost ranked the best at selecting slow-moving areas, followed by Velocity as a Boundary and Velocity as a Feature, and the Base scenario ranked last (Table 2). Results were consistent among emission scenarios (Table 2). For the pairwise comparisons, all planning scenarios differed significantly in minimizing the opportunity cost ($p \leq 6.9$ e10^{-05}) and selecting for slow-moving areas ($p \leq 2.2$ e^{-16}; Tables S3 and S4).

Velocity as a Cost was the most efficient and flexible planning scenario for selecting slow-moving planning units and thus protecting climate refugia (Table 3), achieving the slowest median climate velocity, which was 40.4% slower than that for the Base scenario (Figure 4a). It also outperformed Velocity as a Boundary and Velocity as a Feature (Figure 4a), which when compared to the Base scenario

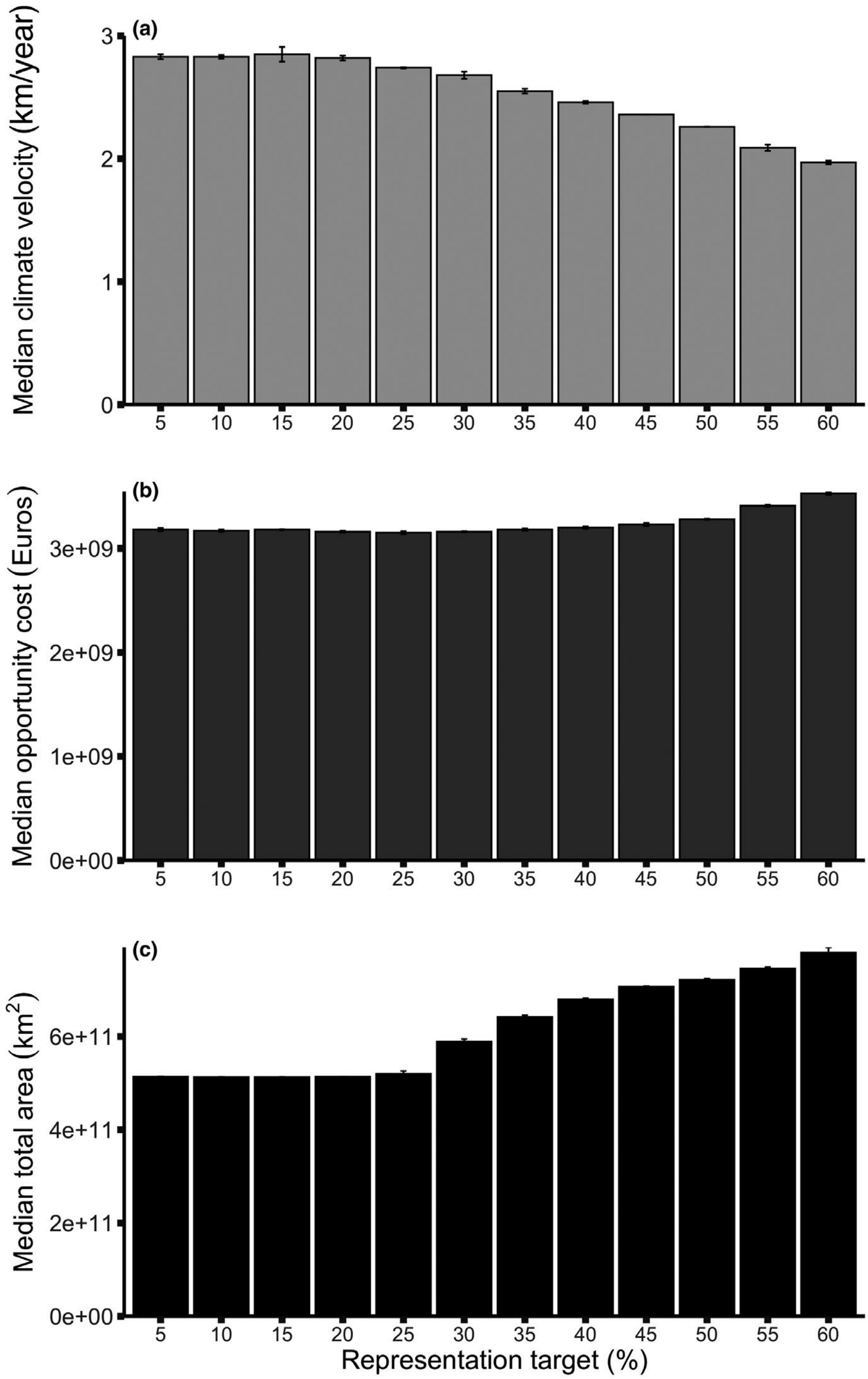

FIGURE 3 Calibration runs for Velocity as a Feature scenario under SSP2-4.5 using the 25th percentile of climate velocities to represent as a feature. (a) Climate velocity, (b) opportunity cost in monetary value and (c) total area from 100 runs (± 95% nonparametric confidence intervals) generated in Marxan

decreased the selection of slow-moving planning units by 15.1% and 2.5% respectively. However, because Velocity as a Cost did not include the opportunity cost, it was least cost-effective (Table 3), increasing the total cost almost tenfold relative to the Base scenario. In comparison, Velocity as a Boundary caused a moderate increase of 7.2% in the total opportunity cost, while the cost of Velocity as a Feature was practically the same as the Base scenario, decreasing 1.1% (Figure 4b).

Velocity as a Boundary had an intermediate performance (Table 3), while Velocity as a Feature was the most cost-efficient, but the least flexible and, of the three climate-smart approaches, was the worst at selecting slow-moving areas. When we calibrated Velocity as a Boundary, we found that increasing the boundary length modifier selects slower moving areas, but that after the initial improvement, the cost increases substantially without much change in the selection of slow-moving areas (Figure 2). We found an improvement in the median velocities of 17.7% and 13.3% when comparing the highest boundary length modifier and the calibrated value for Velocity as a Boundary to the lowest boundary length modifier used in the calibration respectively. Moreover, when

TABLE 2 Ranking in terms of opportunity cost and climate velocity for planning scenarios under three climate scenarios. Values represent median ranking scores for opportunity cost and median climate velocities from 100 runs (±95% nonparametric confidence intervals)

	SSP1-2.6		SSP2-4.5		SSP5-8.5	
Scenarios	Opportunity cost	Slow moving	Opportunity cost	Slow moving	Opportunity cost	Slow moving
Base	124 [106, 142]	338 [327, 350]	128 [111, 146]	352 [336, 360]	124 [101, 148]	350 [341, 358]
Velocity as a Cost	350 [341, 360]	49 [40.8, 61]	350 [341, 360]	50 [36, 66]	350 [341, 360]	51 [41, 61]
Velocity as a Boundary	248 [239, 260]	150 [140, 160]	250 [241, 260]	150 [141, 160]	232 [215, 252]	150 [141, 161]
Velocity as a Feature	83 [68, 97]	254 [238, 264]	77 [64, 93]	260 [247, 269],	91 [74, 108]	250 [237, 264]

TABLE 3 Assessment of the performance of three approaches developed to protect climate refugia. Flexibility is the freedom with which slow-moving planning units can be selected

Scenarios	Selecting slow moving	Cost-efficiency	Flexibility	Recommendations
Velocity as a Cost	Best	Worst	Best	Identifies the best places to protect biodiversity in slow-moving areas. Not recommended, as it fails to minimize socio-economic cost. Flexible because selection of slowest planning units does not constrain the solution to a set of planning units or their spatial aggregation
Velocity as a Boundary	Intermediate	Intermediate	Intermediate	Recommended approach because it best balances finding cost-efficient solutions while selecting slow-moving planning units. Requires calibration of boundary length modifier to choose appropriate trade-off when minimizing cost, compacting the solutions and selecting slower velocity areas (see Figure 2 and Supporting Information). Has intermediate flexibility because selection of slow-moving areas is constrained by spatial aggregation of planning units
Velocity as a Feature	Worst	Best	Worst	Requires a trade-off analysis to determine the representation targets for slow-moving features (see Figure 3 and Supporting Information). However, the performance improves if we increase the representation target, Planners can explore this approach if they can afford an increase in the area of the solution

we calibrated Velocity as a Feature, we found that an increase in the representation target of slow-moving planning units achieved slowest median climate velocities, with little change in the cost, although it substantially increased the amount of area required to meet the targets (Figure 3; Figures S3 and S4). For example, a two-fold increase in the representation target of slow-moving planning units, from 25% to 50%, only increased 4.2% the opportunity cost with a substantial decrease in the selection of slower moving planning units by 17.6%; however, the area of the solution increased by 38.7% (Figure 3). Sensitivity analysis for Velocity as a Feature revealed no improvement when we used alternative thresholds for selecting slower moving planning units to be represented as a feature (Figures S3 and S4).

3.2 | Spatial overlap

The Base scenario had a moderate spatial overlap with Velocity as a Boundary and high overlap with Velocity as a Feature (Figure 5; Table 4). By contrast, Velocity as a Cost exhibited little overlap with any other scenario, while Velocity as a Feature and Velocity as a Boundary had moderate overlap.

3.3 | Sensitivity analysis

The analysis of ranks and subsequent pairwise comparisons revealed similar results for SSP1-2.6 and SSP5-8.5 as we report above for

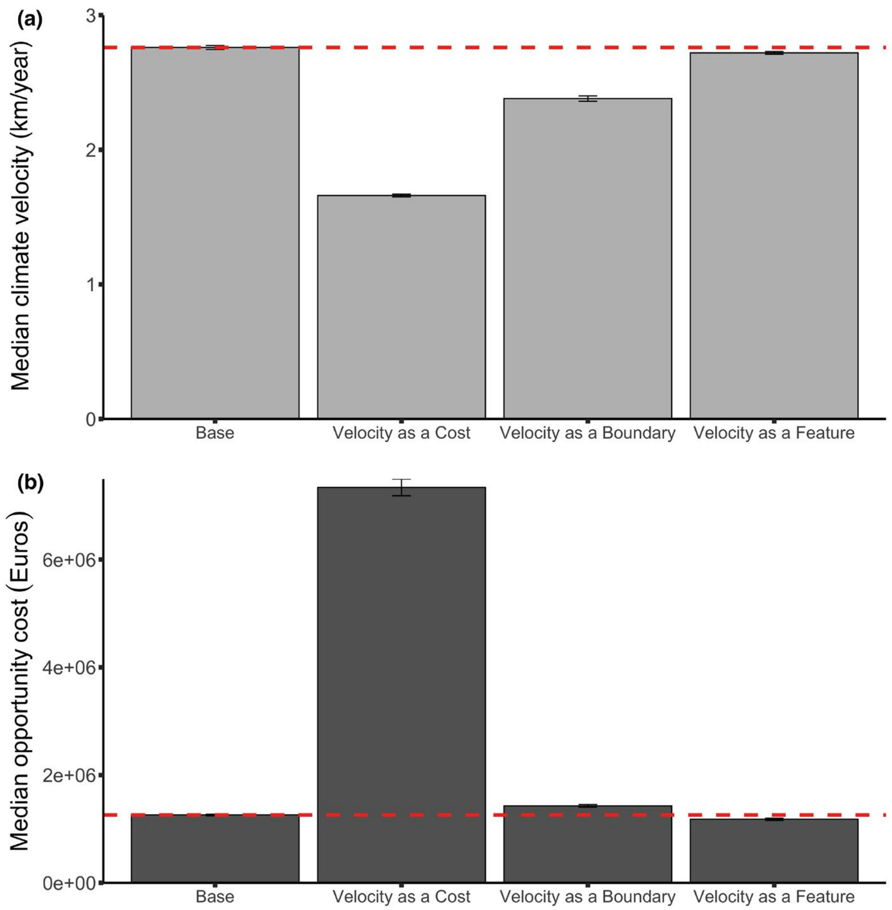

FIGURE 4 (a) Climate velocity under SSP2-4.5 and (b) opportunity cost, Euros from 100 runs (± 95% nonparametric confidence intervals) among Base scenario and scenarios designed to protect climate refugia (Velocity as a Cost, Velocity as a Boundary and Velocity as a Feature) generated in Marxan. The horizontal dashed line indicates the median value (for climate velocity across the 100 solutions) for the base scenario

SSP2-4.5 (Table 2; Tables S3 and S4). The only exception was the comparison between the Base scenario and Velocity as a Feature, which revealed no significant difference in opportunity cost ($p = 0.29$) for emission scenario SSP5-8.5 (Table S3). Qualitatively, Velocity as a Cost remained the most effective and flexible scenario for minimizing the selection of slow-moving areas, compared to the other planning scenarios, but was also the least cost-effective (Figures S5 and S6). In addition, the spatial overlaps followed the same pattern as for SSP2-4.5, with Velocity as a Cost exhibiting little overlap with the other planning scenarios (Tables S5 and S6; Figures S7 and S8). Importantly, there was greater spatial overlap among the planning scenarios within climate scenarios than among the climate scenarios for any given planning scenario (Table 5; Table S7), suggesting that the efficiency of the various approaches is relatively independent of the future climate.

4 | DISCUSSION

We present a range of methods for designing marine protected areas that meet the climate-smart adaptation strategy of protecting climate refugia, among other considerations. A fundamental principle in conservation planning is to identify cost-effective priority areas that meet conservation targets while minimizing potential human conflicts arising from the implementation of marine protected areas (Arafeh-Dalmau et al., 2017; Ban & Klein, 2009). As expected, although networks of marine protected areas that used climate Velocity as a Cost are more efficient at selecting slow-moving planning units, they yield economically inefficient solutions. Both Velocity as a Boundary and Velocity as a Feature perform better—they minimized the selection of slow-moving planning units without dramatically increasing the opportunity cost.

The low degree of spatial overlap between Velocity as a Cost with the other three planning scenarios reinforces the principle that the opportunity cost strongly controls the spatial configuration of solutions (Ban & Klein, 2009; Mazor et al., 2014), and also highlights the need to use approaches that meet conservation objectives while considering both socio-economic data and potential climate impacts.

4.1 | Recommendations

Velocity as a Boundary had an intermediate performance by selecting slow-moving planning units and being cost-effective, proving to be a more desirable approach than Velocity as a Feature at selecting slow-moving areas. However, Velocity as a Feature can outperform Velocity as a Boundary if we increase the representation target for slow-moving planning units, albeit at the expense of increased reserve size. Even if planners can assume the undesirable trade-off of increased area for protection (Stewart & Possingham, 2005),

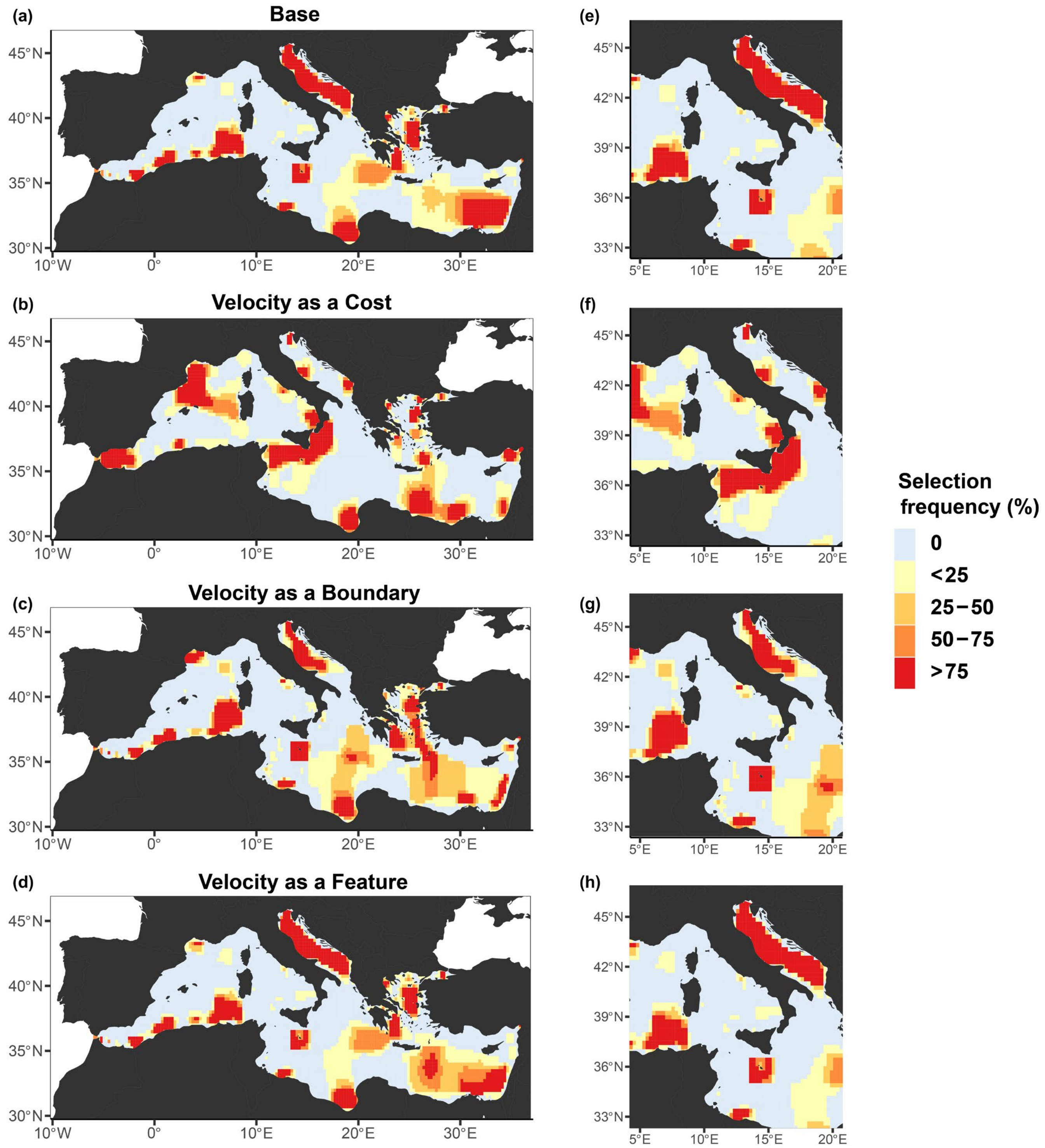

FIGURE 5 Selection frequency under SSP2-4.5 (the number of times a planning unit is selected in 100 Marxan solutions) for the Mediterranean Sea: (a, e) Base scenario; (b, f) Velocity as a Cost; (c, g) Velocity as a Boundary; and (d, h) Velocity as a Feature. For each scenario, we present the full planning domain together with a magnified representation of the west and south coast of Italy and the Adriatic Sea

Velocity as a Feature will not perform much better than Velocity as a Boundary for a similar opportunity cost. An advantage of using Velocity as a Boundary is that it is a more flexible approach for selecting slow-moving areas because it considers all planning units, rather than being limited to a subset classified as 'slow moving', as is the case with Velocity as a Feature. We therefore recommend using Velocity as a Boundary to incorporate climate velocity into marine conservation plans, because it will always find solutions that minimize the overall magnitude of climate velocity without the need for further manipulation. However, this comes with a slight increase in

TABLE 4 Spatial similarity matrix for prioritization approaches under SSP2-4.5. Values represent Cohen's kappa coefficient that ranges −1 to +1, where −1 indicates complete disagreement, 0 represents overlap due to chance and +1 represents complete agreement

Scenarios	Base	Velocity as a Cost	Velocity as a Boundary	Velocity as a Feature
Base	–			
Velocity as a Cost	0.08	–		
Velocity as a Boundary	0.46	0.09	–	
Velocity as a Feature	0.75	0.1	0.5	–

TABLE 5 Spatial similarity matrix for prioritization approaches comparing climate scenarios under SSP2-4.5 with SSP1-2.6 and SSP5-8.5. Values represent Cohen's kappa coefficient that ranges −1 to +1, where −1 indicates complete disagreement, 0 represents overlap due to chance and +1 represents complete agreement

Scenarios	Velocity as a Cost 2-4.5	Velocity as a Boundary 2-4.5	Velocity as a Feature 2-4.5
Velocity as Cost 1-2.6	0.28	0.12	0.16
Velocity as Boundary 1-2.6	0.04	0.55	0.47
Velocity as a Feature 1-2.6	0.08	0.44	0.76
Velocity as Cost 5-8.5	0.49	0.12	0.11
Velocity as Boundary 5-8.5	0.07	0.61	0.5
Velocity as a Feature 5-8.5	0.1	0.48	0.79

complexity of implementation relative to Velocity as a Feature, which could render it less feasible for large study regions with substantial amounts of data. These core methods should be tested, modified and customized according to the context and scale of planning.

Our sensitivity analysis revealed that the performance of the three approaches for incorporating climate velocity and selecting slow-moving areas are robust, regardless of the emission scenario. The spatial overlap analysis suggests that the method used to integrate climate velocity is more influential in controlling the solutions' spatial configuration than is the climate scenario, reinforcing our findings. However, given the uncertainties of Earth System Models (Lotze et al., 2019) and future climate scenarios based on alternative Socio-Economic Pathways (O'Neill et al., 2014), climate-smart conservation requires, among other considerations, the use of multiple climate models and emission scenarios. For this reason, when using our climate-smart approach, we recommend prioritizing those regions that emerge as high priorities regardless of the climate scenario or projection model.

4.2 | Applicability and limitations

The use of climate velocity in spatial prioritization shows that broadly applicable climate-change metrics can be incorporated into the design of networks of marine protected areas, along with other important considerations. However, several caveats remain. For example, climate velocity is best suited for planning at the biogeographic scale or for identifying networks of large marine protected areas (Fredston-Hermann et al., 2018), and it is mainly applied in conservation to identify macro-refugia (Stralberg et al., 2018). Our methods and case study highlight areas in the Mediterranean Sea that are climate refugia and that might minimize future changes in species interactions, which can provide valuable information as initial large-scale prioritization to guide local conservation efforts. As nations initiate negotiations for the Post-2020 Global Biodiversity Framework (CBD, 2020), climate-change mitigation and adaptation are increasingly important considerations. Moreover, in the ocean, most future gains in marine protected-area coverage will need to be in open-ocean waters, both within exclusive economic zones and beyond. This study provides a clear opportunity to incorporate climate velocity to address these needs at broad scales.

Our approach does not incorporate several other aspects of climate change relevant for the design of networks of protected areas. First, climate connectivity is important because it quantifies paths that facilitate species' movement to suitable future climates. One way this could be included is through climate velocity trajectories (Burrows et al., 2014), to create a climate-connectivity matrix and prioritize climate connections following a similar approach to that developed to account for larval dispersal (Beger et al., 2010). Second, because we know that magnitudes and directions of climate velocity differ through the water column (Brito-Morales et al., 2020), this could be captured by incorporating three-dimensional zoning into protected-area policy in the ocean (Brito-Morales et al., 2018; Venegas-Li et al., 2018). Last, because slow-moving areas are not necessarily regions with less impact due to slow warming rates (i.e. areas where climate warming changes less) or less prone to catastrophic events (e.g. heatwaves), our approach does not incorporate a direct measure of climate impact. Therefore, for a conservation plan to be fully climate-smart, we recommend the addition of other measures of impact known to detrimentally affect marine communities (Arafeh-Dalmau et al., 2019; Diaz & Rosenberg, 2008; Kroeker et al., 2013; Smale et al., 2019), such as the magnitude of projected changes in pH and oxygen or marine heatwaves (Oliver et al., 2019).

Finally, it is also important to consider the compatibility of our approach with other aspects of marine protected-area design, such as ecological connectivity among marine protected areas. For example, it is not possible to simultaneously use Velocity as a Boundary scenario with the approach developed to account for asymmetric connectivity (Beger et al., 2010), as both methods modify the boundary length modifier. However, Marxan connect (Daigle et al., 2020), a recently developed tool, allows incorporation of ecological connectivity as a feature, which is compatible with our Velocity as a Boundary approach. In addition, we can simultaneously use the approach of Beger et al. (2010) with our Velocity as a Feature, as this scenario is independent of the boundary length modifier. Further analysis could determine which of these two options are best at selecting slower moving areas while maximizing ecological connectivity among planning units.

Our approaches outlined here provide a framework for climate-smart conservation planning—focusing on refugia—that complements conventional conservation planning priorities, including the representation of biodiversity and the minimization of associated costs. Importantly, our methods depend exclusively on widely accessible data and free-to-use, open-source software, making them available for use in almost any situation and encouraging other research groups to advance the field, with the aim of delivering truly robust networks of climate-smart protected areas by 2030.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

N.A.-D. and I.B.-M. conceived and designed the methodology with inputs from D.S.S., H.P.P., C.J.K. and A.J.R.; N.A.-D. and I.B.-M. analysed the data and D.S.S., H.P.P. and A.J.R. contributed in the discussion of ideas and analyses; N.A.-D. led the writing of the manuscript with support from I.B.-M. and D.S.S. All authors contributed critically to the drafts and gave final approval for publication.

PEER REVIEW

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DATA AVAILABILITY STATEMENT

Data and R scripts are available at Zenodo under the identifier http://doi.org/10.5281/zenodo.3875796 (Brito-Morales and Arafeh-Dalmau, 2020b) .

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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