Received: 14 January 2025 | Revised: 10 September 2025 | Accepted: 16 September 2025

DOI: 10.1111/csp2.70160

PERSPECTIVE

Conservation Science and Practice
A journal of the Society for Conservation Biology
Open Access
WILEY

Conserving climate-change refugia: Insights from research and practice

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Abstract

As the impacts of anthropogenic climate change increase, conservation of climate-change refugia has become a key strategy for effective environmental stewardship. Over the last 5 years, the field of climate-change refugia conservation has made exciting advances, shifting from concepts and theory to refugia mapping and implementation. However, few studies have advanced to action on the ground; while 84% of studies identified and mapped refugia, only 4% involved implementing management action. Moreover, taxonomic and geographic gaps remain, with most studies focused on terrestrial plants and vertebrates in Europe and North America. Here, we outline impediments to implementation following the steps of the Climate-Change Refugia Conservation Cycle. Based on a systematic literature review, we elucidate advances and obstacles with examples from a diversity of systems and sectors from across the world and highlight emerging work bridging the gap between research and implementation.

KEYWORDS

climate adaptation, climate refugia, conservation, knowledge coproduction, landscape planning, microrefugia, resource management, systematic literature review, translational ecology

1 | INTRODUCTION

Changes in the frequency, intensity, and distribution of ecological disturbances such as droughts, floods, wildfires, hurricanes, and sea-level rise are transforming ecosystems and compounding the effects of chronic stressors like increasing temperatures, habitat loss, poor water management, and shifting precipitation regimes (Balaguru et al., 2025; Roy et al., 2023; Turco et al., 2023; Vacek et al., 2023; Wang et al., 2023; Weiskopf et al., 2020; Wiens & Zelinka, 2024). The resources required for responding to these climate change challenges, let alone enacting proactive conservation, appear daunting.

Strategic frameworks such as Resistance-Resilience-Transformation (RRT; Peterson St-Laurent et al., 2021) and Resist-Accept-Direct (RAD; Schuurman et al., 2025) provide the scaffolding for a suite of climate adaptation strategies, from preventing to promoting change. Concurrently, refugia conservation has emerged as an important climate adaptation strategy (Hylander et al., 2022; Keppel et al., 2024; Morelli et al., 2020; Rojas et al., 2022). Climate-change refugia are areas relatively buffered from contemporary climate change that enable the persistence of valued physical, ecological, and sociocultural resources (Morelli et al., 2016). They might allow survival for populations that are either unable to quickly adapt to changes or are not sufficiently mobile to track suitable climate. Efforts are increasing to identify and verify refugia (Barrows et al., 2020) and, more broadly, to integrate refugia better into conservation planning (Kehm et al., 2026; Keppel et al., 2024). As momentum increases around these topics, syntheses on the existing body of knowledge and priorities for future work are needed.

To synthesize the state of climate-change refugia science and identify gaps in research and implementation, we conducted a systematic literature review in ISI Web of Science using the search Topic terms "climate-change-refugia" or "climate-refugia" or "microrefugia" or "climatic-refugia," identifying journal articles published before 4/1/2025. This systematic literature review aims to provide a high-level overview of what has been published, when, for which taxa, and in which geographic regions, rather than an exhaustive analysis of the existing literature or a detailed synthesis of individual case studies. We use it as a foundation to highlight recent advances in refugia science and identify key impediments to refugia implementation (Figure 1), and to highlight potential solutions, using the lens of the Climate-Change Refugia Conservation Cycle (CCRCC; Morelli et al., 2016), a framework to guide the identification, verification, and management of climate-change refugia within broader planning processes.

After excluding 212 papers focused only on paleorefugia (areas where populations or genes persisted over centuries to millennia, especially during the last Glacial Maximum; Harrison & Noss, 2017), we identified 634 empirical studies published from 2008 to early 2025, with about 63% published since January 2020 (Figure 2a). Over half of the studies took place in Europe (257) and North America (214), followed by Asia (163; Figure 2b).

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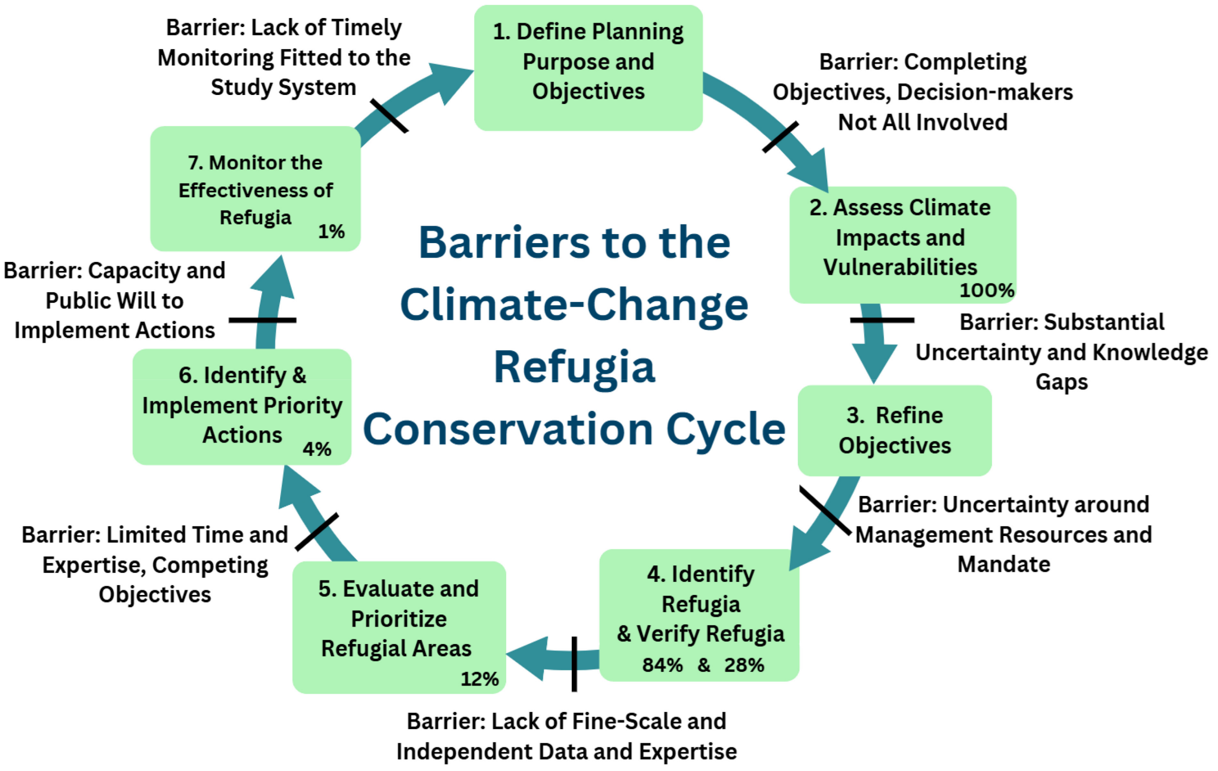

FIGURE 1 The Climate Change Refugia Conservation Cycle (CCRCC; modified from Morelli et al., 2016) and common challenges associated with completing each step. Percentages indicate the proportion of published empirical refugia papers for which that was the most advanced CCRCC step completed). Steps 1 and 3 were rarely highlighted in publications so they are not quantified here.

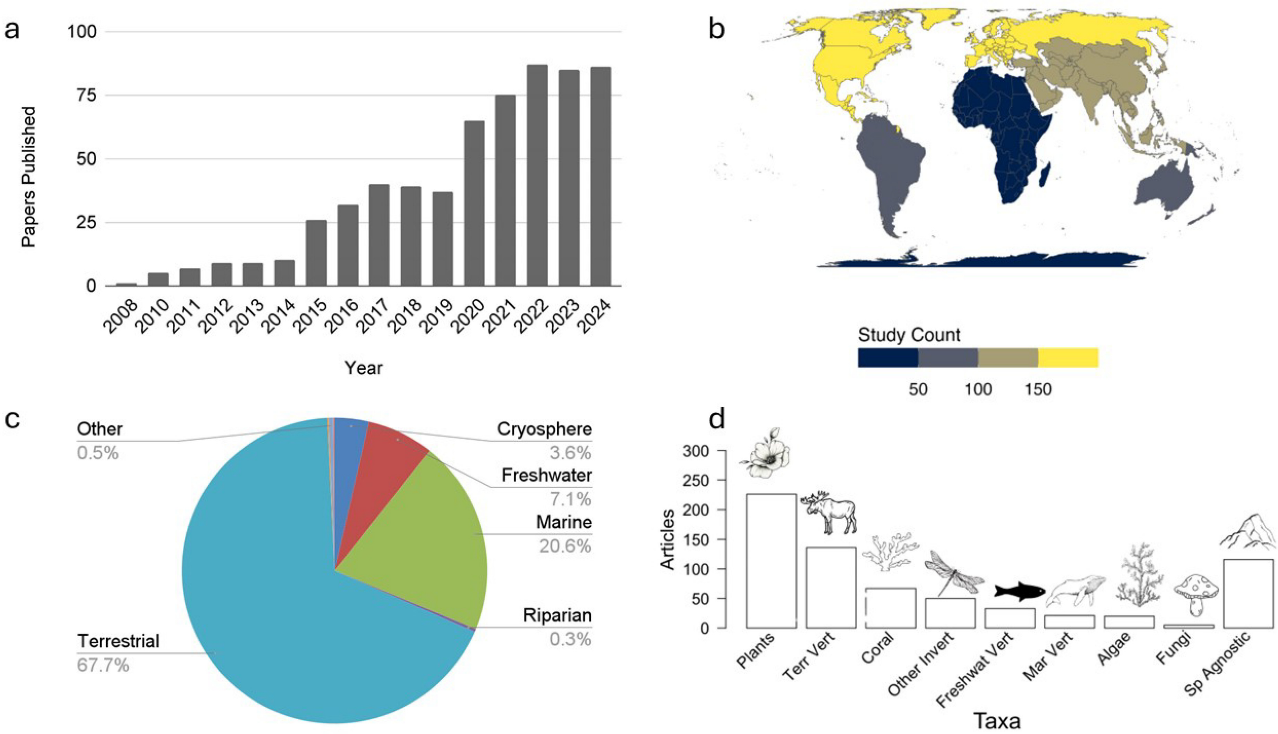

FIGURE 2 Journal articles studying (non-paleo) refugia identified by a systematic literature review, summarized by (a) years of publication, (b) location (continent - some articles covered more than one), (c) ecosystem, and (d) focal taxa.

Two-thirds (431) focused on terrestrial ecosystems, especially plants (225; Figure 2c) and vertebrates (190; Figure 2d). Studies of other kingdoms, in other geographies, and in freshwater, estuarine, and cryosphere environments were underrepresented.

2 | IDENTIFYING AND OVERCOMING BARRIERS TO IMPLEMENTATION

2.1 | Define planning purpose and objectives

The first step in conserving climate-change refugia is to identify the valued resource, often a species or population, for which a conservation or management need has been identified, the temporal and spatial scale for relevant refugia, and what the objective is. This step was rarely highlighted in publications, so we were unable to quantify it explicitly. The process can be challenging if key partners and decision makers are not involved; allocating time and building consensus can help (Kehm et al., 2026). Climate change considerations add another layer of complexity that requires dynamic and future-focused thinking to set specific and measurable objectives (Lawler, 2009; Reside et al., 2018; Watson et al., 2012). Revisiting objectives later in the process (step 3) can provide an opportunity to adjust if progress is too slow or success appears unlikely. To fully engage all partners for input and consensus, a successful planning process will benefit from the deep engagement developed through the paradigms of translational ecology (Enquist et al., 2017) or coproduction of knowledge (Rosemartin et al., 2023). Barriers to this step include competing objectives (e.g., socioeconomic vs. ecosystem values; Reed et al., 2019) and implicit or explicit exclusion of partners and rightsholders (Few et al., 2007; Sovacool et al., 2015).

2.2 | Assess climate impacts and vulnerabilities

The second step in the cycle, which all of the non-paleorefugia articles conducted at least to some extent, involves determining what, where, and how the resource of value, e.g., species or ecosystem, is likely to be most impacted by climate change. Climate change vulnerability assessments (CCVAs) are often used to assess species sensitivity and adaptive capacity based on traits (Foden et al., 2013; Hidalgo-Triana et al., 2023) or correlations between occurrence and environmental variables (Cavalieri et al., 2026). However, a challenge in assessing climate impacts and translating them to management action are knowledge gaps as well as uncertainty around climate projections and how species or systems will respond. Relatively few studies have attempted to evaluate the reliability of CCVAs, and different approaches may produce different estimates of vulnerability (Lankford et al., 2014; Wheatley et al., 2017). Identifying limitations of methodology and uncertainty in expected impacts can help increase applicability and uptake by practitioners. Additionally, weighting CCVA input variables by their relative certainty and providing strategies that yield conservation benefits despite uncertainty (e.g., through co-benefits and win-win situations; Ochiewo, 2022) can help to increase relevance and utility.

2.3 | Refine objectives

After assessing climate impacts and vulnerabilities, conservation goals and objectives (from Step 1) may need to be revised. Refinement can be used to ensure that objectives are realistic, achievable, and scale-appropriate, and to increase the probability of successful outcomes for focal resources as well as partners and rightsholders. However, this step was rarely described in reviewed studies and thus was difficult to quantify explicitly. Challenges occur if there is uncertainty about the resources available to dedicate to management action. This can be particularly true when there are competing priorities and/or organizational or political mandates that are not aligned with the conservation objectives. When necessary, more actionable science can be achieved by revising the number of conservation targets (i.e., habitat types, species/taxa; Choe et al., 2020) or finding suitable surrogates (e.g., if there are data deficiencies or use of ecosystem processes underlying conservation areas; Esralew et al., 2016; Mo et al., 2019) to be more strategic with limited resources. The refinement stage can also involve reassessment of either the spatial or temporal resolution, depending on data availability (e.g., focusing on stream reaches where streamflow data are available rather than an entire watershed or drainage basin; Mozelewski et al., 2026). Because the CCRCC is iterative in nature, goals, are be updated when mandates shift or are clarified, new data become available, and feedback from partners and rightsholders is synthesized within the broader planning process (Cavalieri et al., 2026; Nadeau et al., 2026; Phillips et al., 2026). The challenge to refining objectives centers on uncertainty around management resources (e.g., availability of human resources, budget allocation) and mandate (McCarthy, 2014). Turnover in personnel or government policy especially during this step can prevent projects from being fully realized. Overcoming this barrier requires managing expectations of what is possible given potential fiscal and temporal constraints and finding creative solutions to optimize conservation outcomes (Wu et al., 2021).

2.4 | Map and verify key refugia features

Our literature review indicated that 84% of papers identified and mapped refugia spatially. Mapping enables researchers and decision-makers to link spatial information about resource distribution and vulnerability together to prioritize actions to achieve conservation goals. For example, climate-change refugia can be identified for individual species using species distribution models incorporating future climate (Choe et al., 2020; Morelli et al., 2012; Harrison et al., 2024; Muñoz-Sáez et al., 2021; Sun et al., 2025) or mechanistic approaches emphasizing species physiology and ecological processes (Barrows et al., 2020; Dykema et al., 2026; Hidalgo-Triana et al., 2023). Various methods that integrate remote sensing and spatial models can be used to map regions of historical and anticipated future resistance to changes in temperature or precipitation or climate-mediated disturbance (Cartwright et al., 2020; Morelli et al., 2020; Thorne et al., 2020). Despite the advancements in mapping and modeling approaches that can incorporate climate projections and disturbance dynamics (Cavalieri et al., 2026; Krawchuk et al., 2026; Słowińska et al., 2026), there are still challenges to this step presented by the lack of fine-scale, independent datasets, understanding of species biology (Urban et al., 2016), and expertise to inform the refugia mapping process.

There may be complementarity among refugia identified by using different approaches. Topodiversity metrics can identify environmentally complex regions, for example, within mountain ranges that are likely to harbor microclimates for multiple species, whereas climate velocity and other climatic exposure metrics can be used to identify regions where regional climates change more slowly (Dreiss & Rice, 2026; Michalak et al., 2020; Stralberg et al., 2020). While broad, ecoregion-scale assessments can identify potential refugia for organisms or assemblages of interest, local information is important for understanding resistance potential at scales more actionable for land managers (Ackerly et al., 2020; John et al., 2026). Understanding mapping priorities and selecting appropriate data, or adjusting priorities when data are not available, are important aspects of mapping refugia. Moreover, engaging conservation practitioners and decision-makers regarding environmental covariates, emissions scenarios, and modeling methods ensures that project outputs are relevant for their decision contexts and appropriately encapsulate the uncertainty surrounding future environmental conditions (Enquist et al., 2017). Finally, it is important to map and understand past and current human-driven impacts to potential refugia, as ongoing habitat conversion and degradation can threaten the integrity and resilience of climate-change refugia and undermine their conservation value (Grantham et al., 2019; Monsarrat et al., 2019). However, in some cases, highly impacted or human-modified landscapes may serve as unconventional refugia for species that can persist in urban or peri-urban areas, such as koalas, as fire risk and fire events are typically closely managed in these areas (Hohwieler et al., 2026).

Mapping relies on available and accurate information at scales that are appropriate to the conservation targets and goals, which can be challenging to determine, attain, and reconcile. As technologies have improved, so has the availability, resolution, and quality of environmental and climate data and prioritization methods, although the best products are not always freely available (Fitzgerald et al., 2025). Spatial data to inform refugia identification, e.g., soil and water chemistry or post-disturbance vegetation recovery, can be obtained through spaceborne, airborne, and ground-based remote sensing (Cartwright & Johnson, 2018). Sub-canopy microclimate modeling (De Frenne et al., 2021; Pastore et al., 2025) and topographic downscaling (Estevo et al., 2022; e.g., Holden et al., 2024) based on distributed sensor networks provide additional opportunities to refine climate vulnerability indices (Holden et al., 2024) and species niche projections (Lembrechts et al., 2019; Lenoir et al., 2017). Researchers and planners must reconcile the growing diversity of spatial data, depending on goals and priorities (Carroll & Ray, 2021; Dreiss et al., 2024; Michalak et al., 2020), and synthesize data in a way that is accessible and actionable for managers (Stralberg et al., 2026). Refugia modelers can make the selection of study sites easier by including spatially explicit hypotheses in their maps, such as which areas of a vegetation type's range are expected to retain common climate conditions and which areas are projected to become unsuitable (Halofsky et al., 2024; Thorne et al., 2020). Furthermore, climate-change refugia mapping efforts can better integrate considerations of equity to reflect the intertwined challenge that people and nature face and drive necessary resources to the historically marginalized communities often disproportionately affected by climate change impacts (Hausam, 2024; Kehm et al., 2026; Owen, 2020).

After refugia have been identified, it is important to verify predictions with independent data; however, only 28% of studies carried out this step. Barrows et al. (2020) identified four types of independent data that can be used to test refugia predictions. Two of these types of validation data, areas of high biodiversity/endemism and areas of high genetic diversity, relate to historical refugia (Hampe & Petit, 2005; Maher et al., 2017) but will likely remain relevant under contemporary climate change. The other two data types, physiological traits (e.g., heat or drought tolerance) and demographic rates, can be compared in and out of predicted climate-change refugia (Bentze et al., 2026; McClanahan et al., 2024; Ottaviani et al., 2019; Rivera-Burgos et al., 2021). Independently testing refugia models in these ways can both refine the models and provide important insights for refugia management (Krawchuk et al., 2026), such as improving understanding of species biology (e.g., physiological tolerances) and therefore species management. For example, independent tests of the temperature sensitivity identified by refugia models have revealed the importance of soil moisture in mitigating heat stress for plants, resulting in new management approaches focused on water-holding capacity (Nadeau et al., 2026). Barriers to testing refugia predictions with independent data include lack of capacity; there is often a trade-off between the urgency to implement management and the data collection, time, and expertise needed for independent model verification (Bennett et al., 2018; Lyons et al., 2008; Månsson et al., 2023; Nadeau et al., 2026). One way to overcome this challenge is to codevelop experiments to test refugia predictions without delaying on-the-ground management action (Nadeau et al., 2026). In addition, when validation may not be possible yet, sensitivity analyses can serve to identify how uncertainty can impact refugia management decisions.

2.5 | Evaluate and prioritize refugia

Refugia, though buffered, can still be vulnerable to climate change. The limits of refugia can be evaluated and quantified to improve management but this requires the availability and dedication of expertise, time, and resources (Keppel et al., 2024); only 12% of reviewed papers carried out Step 5. For example, refugia with the greatest capacity to support biodiversity can be prioritized (Keppel et al., 2015), or refugia can be managed as a network that allows migration as limits are exceeded and new refugia appear (Carroll et al., 2018; Ebersole et al., 2020; Morelli et al., 2020). Alternatively, managers can implement strategies of varying intensity to retain, enhance, or design refugia (Bentze et al., 2026; Fairfax & Westbrook, 2024; Keppel et al., 2024). In such cases, it is essential to identify the protection, restoration, or management strategies best suited to a specific refugial landscape and associated conservation goals.

Maintaining current conditions by managing refugia is only one of many possible conservation objectives, including enhancing connectivity, reducing direct impacts on humans and institutions (e.g., air quality, economic effects, public support), and ensuring the continued provisioning of ecosystem services. Competition between these objectives may challenge the prioritization of refugial areas. Formal structured processes such as systematic conservation planning (e.g., Pressey & Bottrill, 2009) can help identify appropriate refugia within a larger conservation strategy and help to navigate uncertainty and knowledge gaps (Ben-Haim, 2023; Lawler et al., 2020; Mozelewski et al., 2026). Additionally, climate-change refugia mapping efforts can better integrate considerations of equity to reflect the intertwined challenge that people and nature face adapting to climate change and drive necessary resources to the historically marginalized communities often disproportionately affected by climate change impacts (Keppel et al., 2024; Owen, 2020).

Another important consideration is that prioritizing climate-change refugia for conservation may mean accepting change or loss in more vulnerable places (Schuurman et al., 2022). However, for certain highly valued resources, managers may not be comfortable with that trade-off and may instead opt to invest in resistance strategies more broadly.

2.6 | Identify and implement priority actions

After refugia are mapped and other objectives considered, the next step is to design and implement management actions that enhance or maintain refugial conditions and reduce barriers or impacts to refugia access or functioning based on the landscape setting and threats from stressors and disturbances (Keppel et al., 2024; Stralberg et al., 2026). However, this step can be hampered by limited capacity or public will to implement the proposed actions; only 4% of studies accomplished this step. It is important that these actions are specific and communicate the relationship between refugia science and management to ensure they are relevant and actionable. Many of these strategies are scale-dependent; for example, grassland macro-refugia may be identified and conserved at regional scales by establishing protected areas and improving connectivity, but managed at local scales, through prescribed burning, altered grazing practices, mechanical restoration, and identifying unique hydrological features (Zuckerberg et al., 2026). Management actions for climate-change refugia can also employ strategies that simultaneously benefit non-refugial targets (e.g., species or habitat types) where they are complementary and appropriate for established conservation goals, especially when staff time and other resources are limited.

The most critical element in bringing refugia science to action is engagement with practitioner communities (Morelli et al., 2016; Rosemartin et al., 2023). Collaboration among government agencies, Indigenous communities, conservation organizations, and private landowners is essential for effective implementation (Choe & Thorne, 2019; Kehm et al., 2026; Stralberg et al., 2026), ensuring that strategies are supported through policies, funding, and on-the-ground actions. The coproduction process may involve examination of refugia maps to identify site-specific actions (Mozelewski et al., 2026; Zuckerberg et al., 2026) and inclusion of local and Indigenous knowledge (Hausam, 2024; Kehm et al., 2026), but it may also link existing system- or species-specific strategies and tactics to the most appropriate places on the landscape (Jennings et al., 2026). Importantly, collaboration can reveal limitations to management to identify actions that incorporate operational, financial, political, and capacity-based constraints (Wright et al., 2020). Finally, an important pathway to implementation is meaningful dissemination of refugia maps and potential management actions, for example through interactive mapping platforms and adaptation menus as well as case studies to demonstrate how refugia maps and strategies can be put into action (Kehm et al., 2026; Krawchuk et al., 2026).

2.7 | Monitor refugia effectiveness

Monitoring and research across different systems and scales is essential for guiding refugia stewardship and conservation efforts but can be difficult to implement promptly or with methods that are appropriate to the system; only 1% of reviewed papers made it to this step and completed the CCRCC. Therefore, setting the context for monitoring at the outset is critical. Understanding the physical, biogeographic, and ecological factors that enable the persistence of refugia and inform adaptive management requires a tailored approach based on the management goals defined in the initial stages of the CCRCC (Morelli et al., 2016). Critical changes within refugia can be best examined through the lens of systematic and integrated monitoring, incorporating multiple lines of inference at multiple scales, and including spatially explicit hypotheses of where and how biodiversity may respond across ownership and management status (Morelli et al., 2020). Remote sensing, in situ monitoring, and modeling have all informed management strategies, and each has advantages and disadvantages (Fridley, 2009). In situ monitoring and manipulative experimentation with data loggers, game cameras, or in-person surveys can provide useful, but often costly high-resolution data (Bentze et al., 2026; Glennon et al., 2019; Phillips et al., 2026). Remote sensing methods using sensor networks, airborne sensors, and/or satellite platforms provide spatiotemporally extensive data but can be too coarse or simplified to inform fine-scale questions, particularly for rare species (Cerrejón et al., 2021). Integrating in situ and ex situ data can produce useful results but often requires expertise beyond agency capacity (Palumbo et al., 2017; Stephenson et al., 2015).

A combination of approaches specific to the context and geography of each refugium or study can allow for a holistic view that can inform management based on different future scenarios of change (Kehm et al., 2026). Robust refugia monitoring schemes would ultimately include: aligning with clear objectives; tracking the rate of change to relevant environmental factors; assessing how climate change affects valued resources (e.g., populations); and identifying the key indicators to incorporate in monitoring after management implementation to track project efficacy.

3 | A NEED FOR INCREASED IMPLEMENTATION

Climate-change refugia science offers tangible opportunities through which to approach conservation in an era of rapid environmental change. By following the steps in the CCRCC, practitioners can more easily identify, manage, and monitor areas that allow biodiversity and other valued resources to persist long-term. Our review quantifies the increasing focus on climate-change refugia science and elucidates the need to move beyond refugia mapping to implementation and monitoring of management actions. Few studies have gotten all the way through the process (but see Nadeau et al., 2026). Moving from conception, ideally in a coproduced manner, through validating refugia maps to executing actions on the ground that are then monitored for whether they achieve established objectives is a rare but required route to climate-change refugia conservation and effectively implementing this climate adaptation strategy. Common conservation challenges related to limitations in capacity and resources, data gaps and uncertainty, and the effective engagement of diverse perspectives in the process all pose barriers to translating science to implementation; there are ways to overcome these obstacles, however (Figure 3). With consideration and adoption of best practices that can address and overcome challenges, the integration of climate-change refugia conservation with other

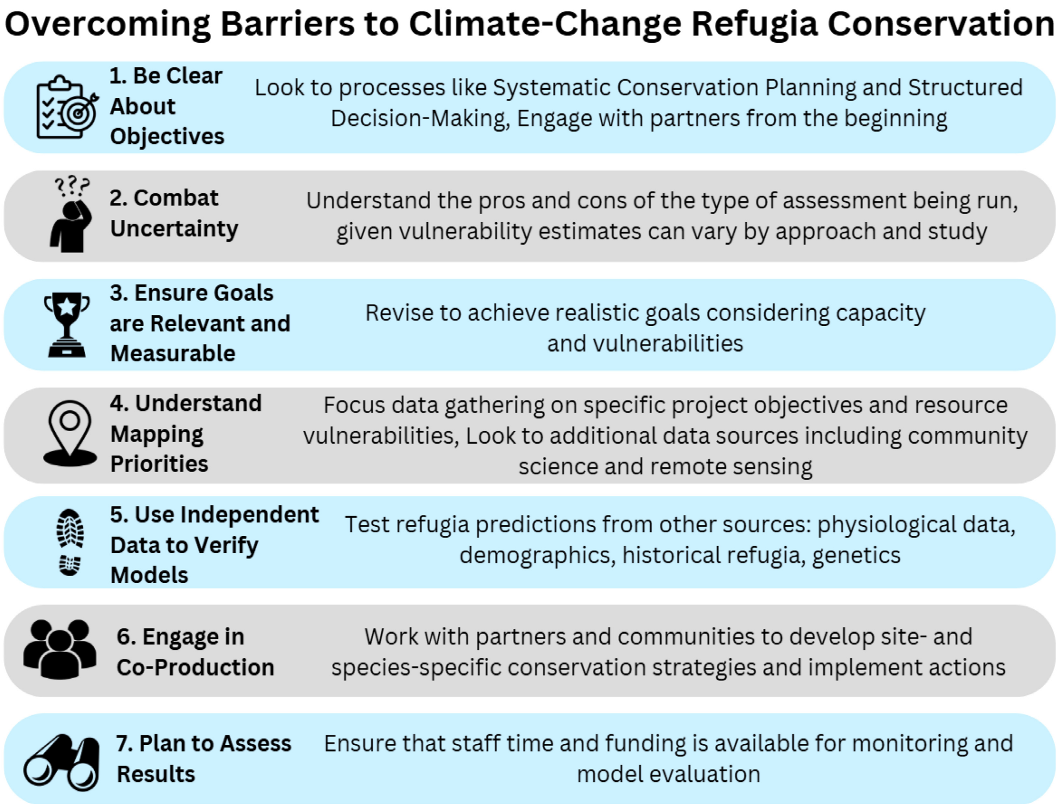

FIGURE 3 Best practices for climate-change refugia conservation.

landscape-level conservation priorities may offer an opportunity to increase implementation rates.

ACKNOWLEDGMENTS

This article, and the special issue that accompanies it, wouldn't have been possible without the energy and dedication and brilliance of public servants, including Connie Millar, to show us the way. We are thankful to a huge slew of reviewers who shared their time and expertise to improve this article and the others in the special issue. Funding came from a variety of sources, including the Northeast Climate Adaptation Science Center. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the US Government.

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How to cite this article: Morelli, T. L., Mozelewski, T., Cavalieri, C. N., Caven, A. J., Dreiss, L. M., Hovel, R. A., Hua, M., Jennings, M. K., John, A., Kehm, G., Keppel, G., Krawchuk, M. A., Langdon, S. F., Lawler, J. J., Lyon, L. M., Meigs, G. W., Mora-Gonzalez, M., Nadeau, C. P., Słowińska, S., … Stralberg, D. (2026). Conserving climate-change refugia: Insights from research and practice. *Conservation Science and Practice*, *8*(1), e70160. https://doi.org/10.1111/csp2.70160