

Article

Climate-Wise Habitat Connectivity Takes Sustained Stakeholder Engagement

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Abstract: Well-managed and connected protected area networks are needed to combat the 6th mass extinction, yet the implementation of plans intended to secure landscape connectivity remains insufficient. The failure to translate planning efforts into effective action (i.e., the research-implementation gap) hinders our ability to conserve biodiversity threatened by ongoing climate change and habitat fragmentation. Sustained collaboration between researchers and practitioners to co-produce conservation strategies can bridge this gap by providing end-users with implementation guidance based on legitimate, relevant, and trusted information. However, few case studies capture methods for the co-production and use of climate-wise connectivity knowledge. Here we describe the framework for sustained engagement used by a multi-jurisdictional practitioner network to co-produce climate-wise linkages for the interior coastal ranges in Northern California. We found iterative co-production shaped ecological objectives, input data, analytical methods, and implementation priorities. Stakeholders used both co-produced and local socio-ecological (e.g., development threat, management priorities) knowledge to finalize corridor implementation plans. Priority corridors afforded greater climate benefit and were more likely to connect lands managed by participant organizations. Our results demonstrate how collaborative partnerships can bridge the gap between connectivity research and implementation. Lessons learned, outcomes, and future plans provide insights to advance landscape-scale resilience to climate change.

Keywords: climate change; habitat connectivity; conservation planning; knowledge use; permeability; research implementation gap; sustained engagement; wildlife corridors; protected areas

1. Introduction

Halting biodiversity loss, as articulated in sustainable development goal 15 (SDG 15) of the United Nations, cannot be accomplished through the existing network of protected areas (PAs) [1]. The need for additional protection as well as ecological connectivity to combat the 6th mass extinction is widely appreciated by conservation scientists and practitioners (e.g., [2–4]). Beyond protecting species and their habitats, protected areas are expected to play a role in mitigating the impacts of climate change on biodiversity [5,6]. Although central to climate change adaptation policies proposed by countries worldwide [7], the long-term conservation potential of PAs depends on their managers' ability to maintain or enhance conditions that promote biodiversity over time. This is of concern because most protected lands will not contain the same climate types in the future that they currently safeguard, suggesting there may be turnover in community composition in PAs worldwide [8].

Changes in climate are causing a global redistribution of species [9,10] that has been observed as shifts, expansions, and contractions of species distributions [11]. Range shifts pose a challenge for

conservation planners because PAs will fail to provide future protection if critical habitats shift out of existing—and static—boundaries [12]. Coordinated functional connectivity between PA networks is necessary to support the large-scale ecological and evolutionary processes essential for biodiversity persistence, particularly in increasingly transformed and fragmented landscapes impacted by climate change [13]. Improving or sustaining landscape connectivity is therefore a primary concern for the effective conservation and provisioning of ecosystem services [14], and is one of the most commonly cited conservation strategies for climate adaptation [15]. However, only about half of the world's protected areas are part of a connected network [16], suggesting the need for additional corridor implementation.

Multiple guidelines exist that detail corridor planning best-practices to inform implementation efforts on the ground (e.g., [2–4]). Projects typically begin by defining ecological objectives and determining what lands will be connected. This step is followed by the selection of the most appropriate input data and algorithm(s) needed to identify existing connectivity pathways, which are then modeled, assessed, and prioritized for implementation [17]. Climate-wise connectivity planning must also assess climate resilience of the PA network and the likelihood of species range shifts over a longer time horizon [18]. Therefore, climate-wise connectivity projects require that those who enact implementation efforts appreciate the concepts of climate resilience and shifting ranges, as well as the uncertainty that accompanies climate models and projections [19].

Connected networks of PAs are critical for biodiversity conservation, but they can only be effective when complemented by supportive social networks charged with their stewardship. For example, in landscapes with diverse authorities need to be involved including for example landowners, government agencies, conservation organizations, or communal land holders [20]. This can create challenges to knowledge legitimacy, the perception of whether knowledge is generated in fair processes that respect the diverse perspectives of stakeholders [21]. Multi-jurisdictional efforts may be hindered by a historical lack of fair or effective engagement, conflicts over policy or funding priorities between resource managers or agencies, or a history of power struggles between resource agencies, private interests, and indigenous communities [22].

Coarse-scale analyses that identify large expanses important for connectivity may inspire regional connectivity concepts, but actionable projects require high-resolution data to guide parcel-scale decisions [2]. In terms of scaling, a disconnect between the scale of the ecological processes of interest and the scale of identification, assessment, and prioritization analyses can result in failure to meet conservation objectives (e.g., [23]). To overcome this challenge, local stakeholders can verify the relevance of considered ecological data sets based on field knowledge, and can also provide a nuanced understanding of the local biotic and abiotic features that is necessary to correctly prioritize the particular species and ecological processes of concern at any single location [24].

As the connectivity implementation process is often nonlinear, a flexible approach is needed to accommodate activities that may overlap in time, feedback loops between key actions, or shifting priorities in response to emerging opportunities or challenges [20]. A purely data-driven connectivity prioritization process might rely solely on an optimization modeling approach to identify priority locations to be conserved. Alternatively, incorporating the perspectives of land managers may allow a holistic evaluation that includes a more experiential understanding of the connectivity potential, important local biotic and abiotic features, and conservation threats [25].

Bridging the Gap through Sustained Engagement

While the number of connectivity plans has grown rapidly over the past three decades [26], the extent to which these plans have been implemented remains circumspect [27,28]. The failure to translate scientifically-informed connectivity plans into effective action falls within the widely recognized research-implementation gap [29], and hinders our ability to conserve biodiversity under the ongoing stressors of climate change and habitat fragmentation [30,31]. However, this gap has been bridged by some dedicated conservation scientists and practitioners (e.g., [32–35]).

Here, we define knowledge as research findings designed to meet the needs of end-users and co-production as the process of collaboration between researchers and stakeholders to develop such knowledge [36,37]. When people are meaningfully involved in producing knowledge, they are more likely to use it for implementation because they consider it legitimate (i.e., equitable and unbiased), salient (i.e., relevant to decision making), and credible (i.e., deriving from trusted and authoritative sources) [21]. The trifecta of legitimacy, salience, and credibility inform the usefulness of co-produced information, and is critical to the success of efforts that aim to translate science to action [38–40].

Collaborative partnerships provide a mechanism for integrating the expertise and needs of the end-user and impart researchers with an increased understanding of the decision-making context that helps bridge the gap between conservation science and implementation. Initiating a collaborative process has been identified as the most important first step in corridor planning and the best way to capture essential local knowledge about the project setting [17]. The process involves a bidirectional exchange that requires researchers and other experts to effectively co-produce credible, relevant information with stakeholders who have the capacity and willingness to actively participate in knowledge creation, inform conservation plans, and translate plans to targeted actions and outcomes [41,42]. Thus, conservation researchers and management practitioners need to work together more closely from the outset to co-produce conservation solutions that are credible, relevant, and legitimate [43] to improve the integration of conservation science and practice (e.g., [44,45]).

Simply bringing researchers and stakeholders together will not result in knowledge co-production in the absence of a skilled facilitator [46]. A backbone organization provides centralized management to support cross-sector partnerships, while also coordinating and enhancing information flow between a collective of diverse participants in light of shared goals and a sensitivity to organizational differences [47]. The role of the backbone organization as facilitator is to help frame and maintain a focus on the collective vision, shape strategies to accomplish shared objectives, and cultivate engagement and ownership across the network. A backbone organization supports the collaboration by facilitating meaningful dialogue, rather than independently setting the group's agenda or pre-determining solutions. If successful, this structure empowers participants with disparate interests and priorities to express their concerns and aspirations for the project [24,48], which in turn generates enthusiasm among stakeholders, and provides momentum for implementation [20].

Related, but distinct, is boundary work to facilitate the use of science by sustaining interactions between science producers and end-users, and by spanning potential boundaries to connect science and policy [49]. Both backbone and boundary organizations may be needed to support the process of developing a common vision of a connected landscape. In the case described below, one organization played both roles in collaboration with University of California Cooperative Extension, but these responsibilities could be fulfilled through a range of partnership structures.

This paper focuses on the sustained approach to stakeholder engagement used by a multi-jurisdictional landscape stewardship network, the Mayacamas to Berryessa Connectivity Network (M2B), between 2014 and 2018 to co-produce a climate-wise connectivity knowledge base and road-map for the Inner Coast Ranges of California. We present research into how sustained engagement (1) influenced the knowledge exchange between and among stakeholders and researchers; (2) shaped the use of knowledge by stakeholders, including ecological objectives, data, analysis, and results; and (3) informed the conservation outcomes for increased resilience of a protected area network. The technical modeling methods and regional results for the climate-wise connectivity assessment are described in Gray et al. [50].

The primary research questions are:

- How did the climate benefits of priority corridors identified by stakeholders at the project outset compare with the final corridors prioritized through the co-production process?
- How did other characteristics of the corridors change throughout the process?
- How does the composition of the participating stakeholders influence the outcomes of the corridors?

In this paper, we first describe the M2B Network and project framework and provide a summary of key project activities and facilitation methods that led to measurable outcomes using examples from the stakeholder engagement process and the co-production of data. Next, we examine the corridor prioritization process and determine whether knowledge that was co-produced through participation in the M2B Network affected the locations prioritized for corridor implementation. We conclude with examples demonstrating the relevance of co-produced outputs to desired outcomes for climate-wise connectivity. The information presented here are reflections from the backbone organization on the process.

2. Materials and Methods

2.1. Project Area

M2B's geographic domain is a 11,670 km² region of Northern California that is bounded by U.S. Highway 101 to the west and the Central Valley to the east (Figure 1). The project area spans 10 county boundaries; including Sonoma, Napa, Mendocino, Lake, and Solano; and encompasses 45 incorporated towns and cities, with a total estimated population of 1,588,002 [51]. Mountains of the Inner Coast Ranges provide spines of wilderness, characterized by globally significant biodiversity, that radiate from rapidly urbanizing regions of the San Francisco Bay Area [52]. These ranges also frame wine-country valleys that support agriculture and tourism industries. The mosaic of protected areas and working lands across the region provides critical support for long-term health of plant and wildlife populations, yet faces ongoing stressors from habitat fragmentation, climate change, drought, and catastrophic fire [53]. Approximately 60% of the landscape (4710 km²) is privately held [54,55]. Protected lands spanned a range of management types that align with the International Union for Conservation of Nature (IUCN) protected area categories [56], including wilderness areas, a national monument, habitat and species management areas, and protected areas with sustainable use of natural resources.

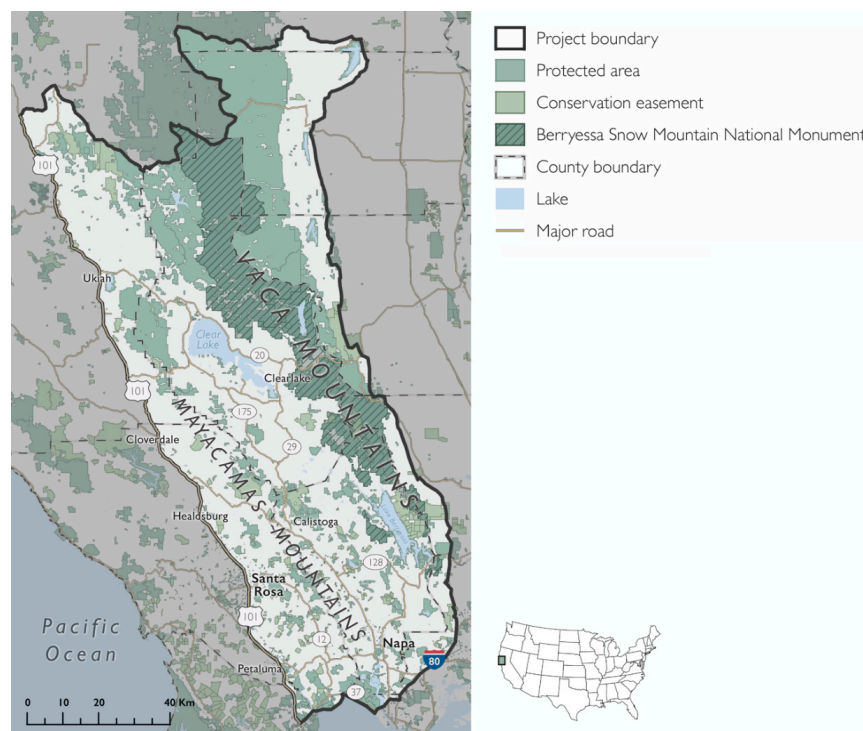


Figure 1. Map of the Mayacamas to Berryessa project area spanning the Mayacamas and Vaca Mountains, overlaid with protected areas (green).

2.2. Project Framework

The M2B climate-wise connectivity assessment conducted in 2017–2018 relied on a framework adapted from Keeley et al. [20] (Figure 2). The framework details activities that enable successful implementation of scientifically informed connectivity planning. It consists of six components: stakeholder engagement; clear ecological objectives that drive data and analysis; opportunities and challenges to address; strategies to ensure project success; conservation outcomes that sustain partner commitment; and monitoring and project evaluation. Additionally, we used an iterative approach to collectively design the ecological objectives, select data, and conduct analyses to prioritize conservation actions with the stakeholders. Specific group tasks were to (1) define ecological objectives, identify relevant input data, and determine analytical methods, (2) prioritize linkages for implementation, (3) quantify the climate benefit of the network with the linkages, and (4) provide data products and relevant outreach materials to accomplish corridor implementation.

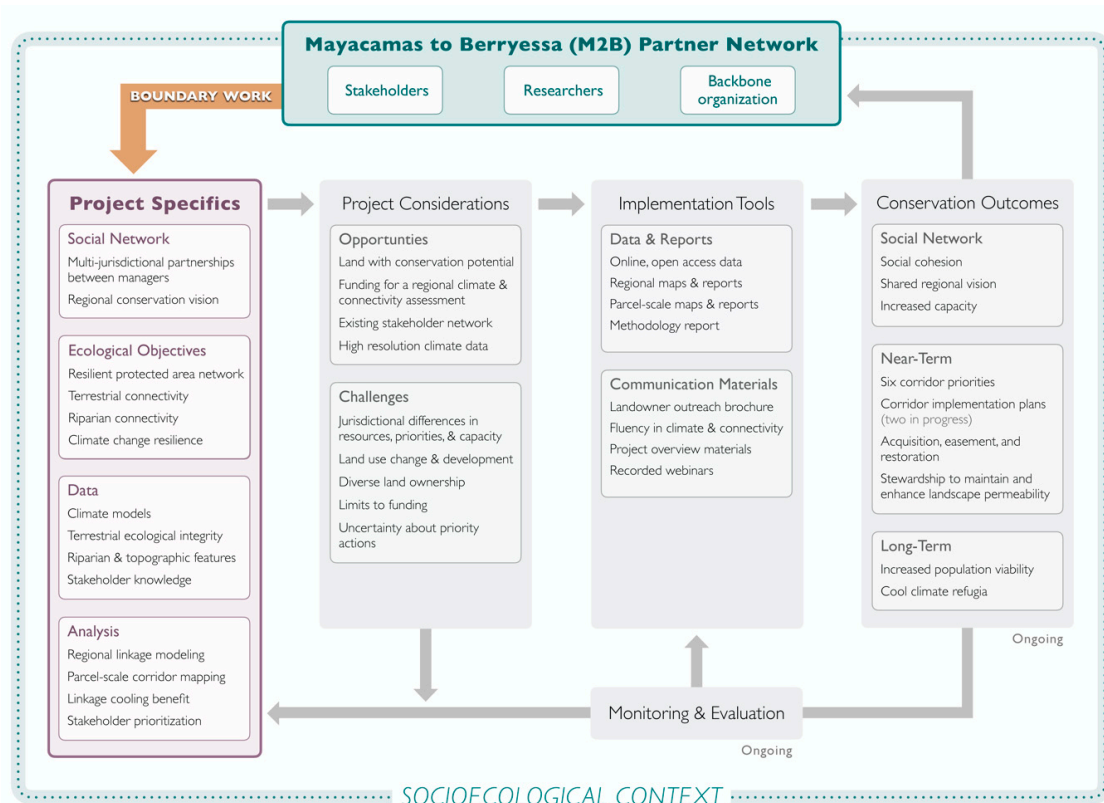


Figure 2. Adapted from the framework outlined in *Making Habitat Connectivity a Reality* (Keeley et al. 2018); Mayacamas to Berryessa (M2B) Network (green), boundary work (orange), and the project specifics addressed in this paper (purple). Resulting conservation outcomes are ongoing, along with monitoring and project evaluation.

2.3. The Mayacamas to Berryessa Connectivity Network and Partners

The Mayacamas to Berryessa Landscape Connectivity Network (M2B Network) is a large landscape stewardship group focused on advancing landscape-level conservation for climate resilience in Northern California's Inner Coast Ranges. The M2B Network and the climate-wise connectivity assessment described in this paper emerged as an intertwined regional strategy to bridge a research-implementation gap that can be attributed to a lack of credibility, salience, and legitimacy stimulated by earlier connectivity assessments. Specifically, practitioners considered a 2013 regional connectivity assessment for the nine-county San Francisco Bay Area [57] to lack salience, as the scale of the analysis

excluded too many resources of concern from consideration. A parcel-scale connectivity analysis conducted for a portion of the Mayacamas Mountains [58] was considered appropriate in resolution, although stakeholders highlighted a remaining need for climate resilience metrics and information that included a consideration of riparian resources as connectivity pathways. Additionally, these data would be most useful for a larger geographic extent than the Mayacamas Range to capture more variability in topography, ecology, and human land use between the recently created Blue Ridge-Berryessa Snow Mountain National Monument and northern reach of the San Francisco Bay.

This strategy was informed and adopted by members of an informal group called the Mayacamas Forum, which met regularly to enhance communication and information sharing between neighboring organizations, landowners, and interest groups based in the Mayacamas Mountains and surrounds. The local non-profit, Pepperwood, a scientific research and education organization, facilitated the Mayacamas Forum and worked with participants over a three-year period to develop a collective proposal and secure funding from the California Landscape Conservation Partnership's Place-based Climate Adaptation Program in 2016.

Pepperwood served as the backbone organization and partnered with University of California Cooperative Extension to do the boundary work, including stakeholder-directed research and analysis support [59]. Annual technical review of the M2B methods and results was provided by an interdisciplinary group of scientists experienced in knowledge co-production for conservation applications, the Terrestrial Biodiversity Climate Change Collaborative (TBC3).

M2B participants were self-selected based on interest in the topic, and can be classified as follows (number of people in parentheses):

- Partner organization (10): Staff from organizations working to preserve and protect open space and natural resources in the counties of Napa, Lake, and Sonoma. Land trusts (3), open space and park districts (2), non-profit organizations (2), a federal agency (1), and university research reserves (2). With the exception of the federal agency the ongoing efforts of partner organizations were restricted to locations within their county boundary.
- Stakeholders (17): Practitioners at partner organizations who worked in one of the following six primary roles: land and resource management (6), conservation planning (6), data analysis (2), operations (1), research (1), and stewardship (1).
- Researchers (3): Academic and non-profit scientists who served as subject matter experts in landscape ecology and climate-wise connectivity, geospatial modeling, and hydrology.
- Managers (3): Members of the backbone organization, also trained scientists, who facilitated stakeholder engagement and project management.

2.4. Stakeholder Engagement

The backbone organization fostered legitimacy through a facilitative approach that emphasized transparency, mediation as a vehicle for decision-making, and sustained engagement among stakeholders working for a range of organizations and jurisdictions. Stakeholders shaped the management framework; and contributed to the development of project expectations, timelines, communication format, and participation structure. To maintain interpersonal connection across a regional project extent, managers used an online project management tool for sharing correspondence and interim products, and also conducted screen-sharing webinars between in-person meetings.

Knowledge interplay can be more effective in a setting in which relevant ecological and political contexts are represented and treated respectfully through dialogue with stakeholders [60]. The backbone organization interacted and iterated regularly with stakeholders to ensure the concerns and perspectives of different stakeholders were actively solicited and incorporated. Information about specific management needs, conservation priorities, and constraints were solicited pre-project using a survey conducted during one-on-one semi-structured interviews with each stakeholder (Supplementary Material, S1). Findings were presented at a collective meeting so all participants could reflect on, and add to, the conservation priorities and challenges/concerns identified by the

respondents, and summarized in a composite table. Managers also solicited feedback through ongoing conversations as well as focused training and data exploration sessions.

To facilitate the effective creation of knowledge to inform climate-wise connectivity implementation, the M2B Network convened quarterly in-person workshops in 2017 and 2018. Convening was a key avenue for network collaboration; the regular meetings provided an ongoing forum for discussing the perspectives, concerns, and values of the individual participants and the M2B Network as a whole. Each convening had a specific topic related to the sequence of project activities. Researchers presented proposed methods and preliminary results during convenings, and managers facilitated conversations to allow knowledge exchange between stakeholders and researchers. Additionally, researchers shared background information about the methods and input data, and answered technical and scientific questions, which fostered credibility. Stakeholders reviewed the presented material, asked clarifying questions, and provided feedback based on their local knowledge.

The facilitation and mediation provided by the backbone organization was critical during the iterative corridor prioritization process. Key to mediating this process were the multiple in-person and web-based meetings to ensure all voices were heard, and the process through which corridors were prioritized for implementation was equitable. Managers guided dialogue to address the specific factors identified by individual stakeholders while delimiting candidate corridors and account for the differing management challenges and socioeconomic constraints among partner organizations.

At the project outset the researchers and managers identified locations of pre-existing concern to each stakeholder. These *a priori* corridors were selected based on each stakeholder's existing knowledge and understanding of the landscape, before the connectivity or climate assessments were conducted. During the first M2B Network meeting stakeholders were asked to identify specific locations they considered important for the long-term maintenance of connectivity on a regional map that was projected onto a screen. This information was captured by having stakeholders draw a rectangle completely surrounding each location. Each rectangle was drawn freehand, then subsequently digitized into a spatial polygon. The resulting *a priori* corridors were used at the completion of the project as a counterfactual to explore how participation influenced locations prioritized by stakeholders.

Each general location prioritized by the project team was refined by a corridor-specific subcommittee that included researchers, managers, and stakeholders from organizations with protected lands within or near final corridor boundaries. Through multiple iterations, each subcommittee delimited a final corridor boundary based on a collection of specific parcels designated for conservation action. For example, the first version of each final corridor boundary was centered on a regional least cost path and was composed of parcels based on the footprint of the corresponding terrestrial linkage. However, researchers adjusted the spatial extent of the boundary in response to feedback from stakeholders, and to accommodate land-use change, such as recent land conversion to vineyards that had occurred since the creation of the ecological integrity data used to generate terrestrial linkages.

Cross-disciplinary experiences that deepen mutual understanding between researchers and practitioners can build relationships that promote the open dialogue needed for effective knowledge exchange [60]. Thus, facilitated convenings with the M2B Network were used as a forum to advance funded objectives while fostering growing social cohesion among stakeholders. The time of day, convening duration, break schedule, and meeting content were intentionally crafted to create an environment that would enhance interpersonal connections and camaraderie between participants. For example, three unstructured breaks were provided to create space and time for participants to interact, allow stakeholders to process technical details, and formulate questions that could be subsequently raised with the group. Additionally, the location for each convening was rotated to introduce team members to protected areas across the M2B Network that exemplified locations important for climate-wise connectivity. Each partner organization hosted the M2B Network at or near a managed property (e.g., a preserve), which ensured at least one convening would be local for each stakeholder and eased the travel burden for a team working across an approximately 12,000 km² project area. Hosts offered guided, post-meeting nature walks, which provided the opportunity to

connect socially in a setting that embodied a shared value—namely, an appreciation for nature and biodiversity. This entire structure was itself co-created with participants.

3. Results

3.1. Ecological Objectives

Five of the ten partner organizations completed the pre-project survey (see S1 for survey questions) and interview. Across respondents, five indicators of conservation priority were identified: geological complexity, hydrologic integrity, animal species, plant species, and prominent landscape features (Table 1). All respondents noted the conservation value of serpentine habitats and endemic alliances, and also emphasized the importance of water supply and quality. Four overarching concerns and challenges voiced by stakeholders were habitat fragmentation, ongoing human impacts, climate change, and socio-economic constraints.

Table 1. Summary of the types and examples of conservation priorities, and concerns and challenges, provided by stakeholders during pre-project interviews (see S1 for survey questions).

Category	Indicator	Examples
Conservation priorities	Geological complexity	Serpentine soils and/or habitats Volcanic soils
	Hydrologic integrity	Water supply and quality Wetlands Riparian ecosystems Geysers and springs Vernal pools Headwaters
	Animal species	Mesocarnivores and large mammals Threatened and endangered species Endemic and/or freshwater fish Rare aquatic and terrestrial invertebrates Amphibians
	Plant species	Rare serpentine endemics Old-growth forest Native vegetation (e.g., grasslands)
	Prominent landscape features	Clear Lake—A large water body in Lake County that provides irreplaceable economic, recreation, and hydrologic services. Mount Saint Helena—A large, centrally located mountain protected by a mosaic of numerous protected areas.
Concerns and challenges	Habitat fragmentation	Land conversion for vineyards and/or cannabis Rural subdivision Roads that impede wildlife movement Fences that are not wildlife-friendly Renewable energy development
	Ongoing human impacts	Recreation on protected lands Agriculture, viticulture, and grazing Wildlife-vehicle collisions
	Climate change	Species loss and mortality Shifts in habitable climate space Invasive species Impacts on water resources (e.g., drought, flooding) Sea level rise Increased wildfire threat
	Socio-economic constraints	Lack of resources (e.g., funding, capacity, data) Social and/or political priorities

The interviews highlighted differing socioeconomic constraints among partner organizations and educated project managers about equity issues within the M2B Network. For example, the availability of financial resources differed between organizations; some lacked dedicated funding whereas others received federal or county (i.e., special district) support. This disparity was compounded by economic differences between Lake, Napa, and Sonoma Counties. The estimated poverty rate in Lake County ranges from 10% to 80% higher than in Napa and Sonoma counties, respectively [61]; while on average,

median property values are 70% lower in Lake County. These differences translate to disparate goals, challenges, and regulatory environments among the three counties. Additionally, the threat of development (e.g., land conversion to vineyard or cannabis farm) may vary with potential economic need and/or benefits.

At the beginning of the funded work (early 2017) the M2B Network finalized its membership and the ecological objectives to align with those outlined in the proposal. The stakeholders emphasized the need for data at two spatial scales to prioritize corridors: (1) a continuous assessment of connectivity across the landscape (i.e., instead of derived corridor pathways), and (2) local information to inform conservation planning and management that occurs on the parcel scale. To provide stakeholders with regional information, the researchers assessed connectivity and identified a potential linkage network resulting in a continuous linkage potential surface across the landscape. The resulting regional linkage network was used for a subsequent climate assessment that evaluated current and future temperature projections and quantified metrics of climate resilience [50]. A subset of linkages in the regional network were then prioritized by the stakeholders for a parcel-scale evaluation, in which researchers quantified the conservation and climate resilience value for individual parcels and generated summary reports to facilitate site-specific corridor implementation.

Although stakeholders acknowledged the importance of maintaining regional connectivity, an understanding of the connections between the lands they manage was considered more relevant for local application. As a result, the researchers conducted a node-based linkage assessment of structural (i.e., species-uninformed) connectivity to identify landscape connections between PAs. The approach used was species-independent in response to stakeholder-expressed concern about maintaining overall ecological connectivity at the landscape scale [50]. Based on input from the stakeholders, we developed a novel riparian permeability surface to use as input for a riparian connectivity assessment. The M2B Network collectively decided that the terrestrial and riparian assessments would remain independent data products to preserve the distinct patterns of connectivity afforded by the two linkage types.

Stakeholder input directly informed the selection of projected climate futures, forecast models, and variables used for the climate resilience assessment based on decisions that emphasized the utility and clarity of the resulting data products. When presented with the options of mid-century (2040–2069) and end-of-century (2070–2099) as future time periods [62], the consensus among stakeholders was results for mid-century would be more impactful as the timeframe was better aligned with strategic planning activities. Although the M2B Network initially evaluated three climate models (CCSM-4, CNRM-CM5, and MIROC-ESM), the group elected to use a single, intermediate, climate model (CNRM-CM5) to focus the assessment and decrease the number of resulting data products. In contrast, stakeholders appeared more tolerant of multiple data products for temperature metrics, of which two were included. Although the use of average annual temperature was initially considered as the sole climate metric, the M2B Network elected to use seasonal temperature extremes for summer and winter in the climate resilience analyses. Stakeholders shared that the differences between the trends for seasonal temperatures resonated with their experiences, and were therefore more readily internalized, and noted that these factors increased their confidence in communicating the material.

To quantify the contribution of each linkage to the climate resilience of the network, we measured the cooling benefit for all delineated linkages based on summer maximum and winter minimum temperatures. We defined cooling benefit as the net difference between the temperatures at two or more locations within a designated area, reported in degrees on a temperature scale (i.e., °C or °F). Cooling benefit has been used to map priorities for climate-wise connectivity at the scale needed for implementation by local land conservation organizations (Gray et al. 2020). Cooling benefit was well-received by stakeholders as an indicator of resilience to climate change; and noted the use of a simple calculation, the clear visualization of results, and a straightforward verbal explanation as positive attributes of the metric. Therefore, we used the cooling benefit provided by each linkage to the PA network as the primary metric of resilience to climate change.

We developed a glossary for consistent communication about connectivity and climate change that was used throughout the project (Supplementary Material, S2). The glossary provided a convenient point of reference that increased stakeholder fluency and helped stakeholders understand the management implications of the connectivity and climate data. For example, the team defined project-specific terms to distinguish between permeable habitat with connectivity potential (i.e., a *linkage*) and a spatially explicit collection of parcels designated for conservation action (i.e., a *corridor*).

3.2. Corridor Prioritization

The M2B Network iteratively delimited corridors in three distinct phases. Phase 1 occurred at the start of the project (i.e., before participating in the connectivity and climate assessment). During phase 1, stakeholders demarcated *a priori* corridors, which were locations of concern for habitat connectivity at the project outset. Phase 2 took place after stakeholders participated in the climate-wise connectivity assessment. In phase 2, stakeholders identified candidate corridors as local regions prioritized for implementation during a researcher-guided exploration of the regional M2B connectivity and climate. In phase 3, final corridors were delimited by parcel boundaries following a collective review of candidate corridor locations.

Fifteen *a priori* corridors of consistent size were identified as important for habitat connectivity by stakeholders at the project outset (mean = 82 km², range: 51–92 km²). The distribution of draft corridor location spanned approximately 60% of the north-south extent of the project area; none were identified within the northernmost reach of the project area.

After the regional analyses were complete, researchers and managers met with stakeholders individually or in small groups (i.e., by organization) to delimit local areas considered priorities for implementation. A researcher-guided exploration of the climate and connectivity data was used as a starting point, and stakeholders were encouraged to share relevant management priorities, identify locations with species or habitats of concern, and consider known or potential implementation challenges or opportunities (e.g., proposed development projects, land use incompatible with wildlife movement) throughout the process. The series of working sessions resulted in a set of candidate corridors recommended for implementation. Readily available satellite imagery base maps that enhanced the relevance of the overlay regional data products were an unexpected boon during working sessions. The use of imagery maps as an underlay increased the relevance of the data exploration by providing stakeholders with a familiar view of the landscape directly beneath potential linkages.

A total of 10 candidate corridors were delimited during the guided data exploration working sessions. The locations identified by stakeholders as conservation priorities changed as a result of the project (Figure 3). Compared to *a priori* corridors, the area of candidate corridors had much larger values for mean and range (mean = 531 km²; range: 92–2133 km²) but a more restricted distribution of locations. Specifically, candidate corridor locations spanned approximately 50% of the north-south extent of the project area and were densely clustered in the middle, where six candidate corridors showed partial or complete overlap. The regions selected repeatedly were not previously identified as *a priori* corridors. We observed a general negative trend between candidate corridor size and the number and total area of properties owned or managed by the partner organization(s) involved in the selection process. Specifically, candidate corridors that were proposed by stakeholders working within organizations that oversee more properties were smaller, and larger candidate areas were associated with organizations with fewer properties.

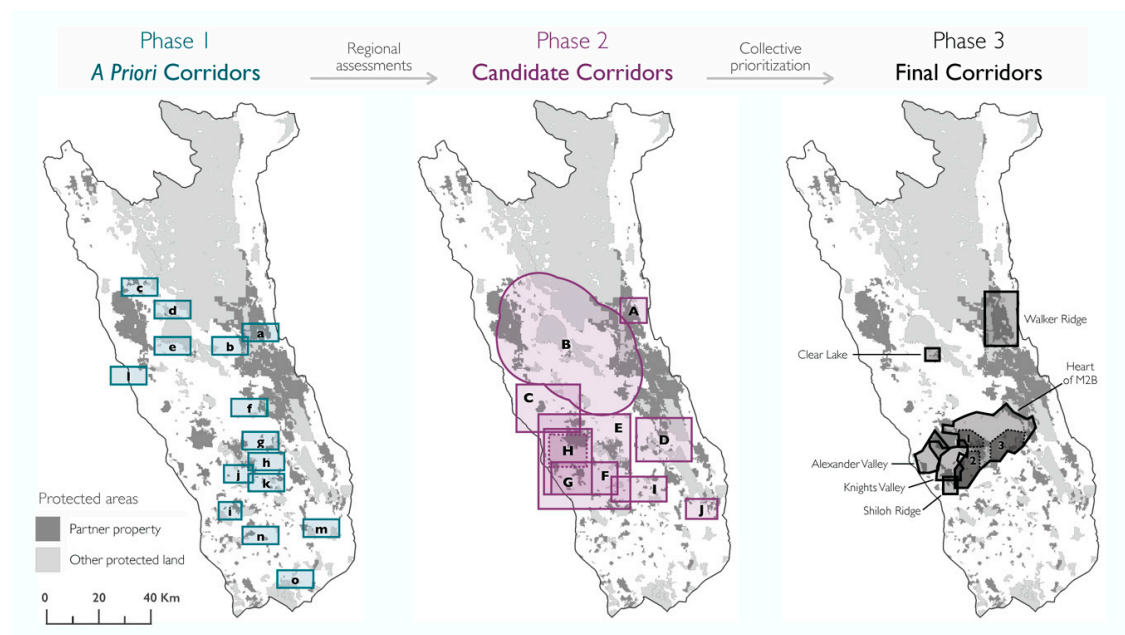


Figure 3. Maps showing the locations delimited by stakeholders during the three phases of corridor prioritization overlaid on protected areas managed by partner organizations (i.e., partner properties; dark gray) and other protected lands (light gray) in the Mayacamas to Berryessa Connectivity Network project area; a priori corridors (blue), candidate corridors (purple), and final corridors (black).

Sixty-seven percent of a priori, and 80% of candidate, corridors were retained within the six final corridors. Five a priori corridors and two candidate corridors were not prioritized during subsequent phases. Land that would contribute to the Alexander Valley final corridor was not identified as an a priori corridor but was added in Phase 2 as candidate corridors G and H. The specific geographic extents ultimately captured within final corridors represents a combination of a priori and candidate corridors (Figure 4). For example, six a priori corridors (a–f) were encompassed within the single candidate corridor that resulted in the Clear Lake final corridor. Additionally, portions of a priori corridor a were included in candidate corridors A and B.

The M2B Network collectively reviewed all candidate corridors and prioritized final corridors that would be used for a detailed parcel-scale climate and connectivity analysis and companion summary report. The time-intensive analyses and reporting for each final corridor necessitated that the M2B Network restrict the total number of final corridors to six. Although considered areas in need of climate-wise connectivity, stakeholders opted to exclude two candidate regions in favor of a large corridor that spanned the three counties and connected the lands managed by most partner organizations. They also prioritized linkages that were connected to lands managed by the partner organizations. Specifically, 97% of final corridors provided connectivity for at least one partner property and most connected two partner properties (82%). In comparison, only half of all the linkages analyzed provided connectivity between two partner properties (54%).

Although adequate for delimiting corridors with a small geographic extent or containing a single terrestrial linkage, working with the refinements made by the subcommittees was insufficient to address site-specific challenges posed by final corridors (Table 2). The use of a distinct, customized approach was required when delimiting a corridor that was situated among numerous, adjacent nodes (i.e., protected lands); that was near a single large node; and that was composed of multiple linkages spanning a large spatial extent. Researchers made these key adaptations iteratively in response to specific challenges identified by stakeholders during the ongoing and collaborative development of each final corridor.

Final corridor boundaries were subsequently reviewed and named by the M2B Network (Table 3). Creating and assigning names to each corridor were not activities defined in the formal project plan, yet were critical in ascribing place-based relevance and creating a shared vision for each corridor. When each steering committee was delimiting final corridor boundaries, researchers initially referred to the corresponding corridor based on the lead stakeholder organization(s). The management team recognized that these labels were a disservice to the team of stakeholders invested in each corridor, and worked with each steering committee to create an official name that resonated with the group. Five of the six resulting corridor names were based on nearby, prominent landscape features; four corridors were named after a ridge (2) or valley (2), and one was named after a lake. The sixth and largest corridor was named the Heart of M2B—a name that was both a geographical descriptor and a metaphor for the landscape and social connections afforded by the corridor. Geographically, the Heart of M2B corridor was located at the center of the project area and spanned the east-west extent of the project area to connect the Mayacamas Mountains with the southern reach of the Berryessa Snow Mountain National Monument. Because the corridor was roughly situated at the intersection of Lake, Sonoma, and Napa counties; and encompassed lands managed by each partner organization; collaboration among all stakeholders was necessary to delimit the boundary and will be essential for future implementation.

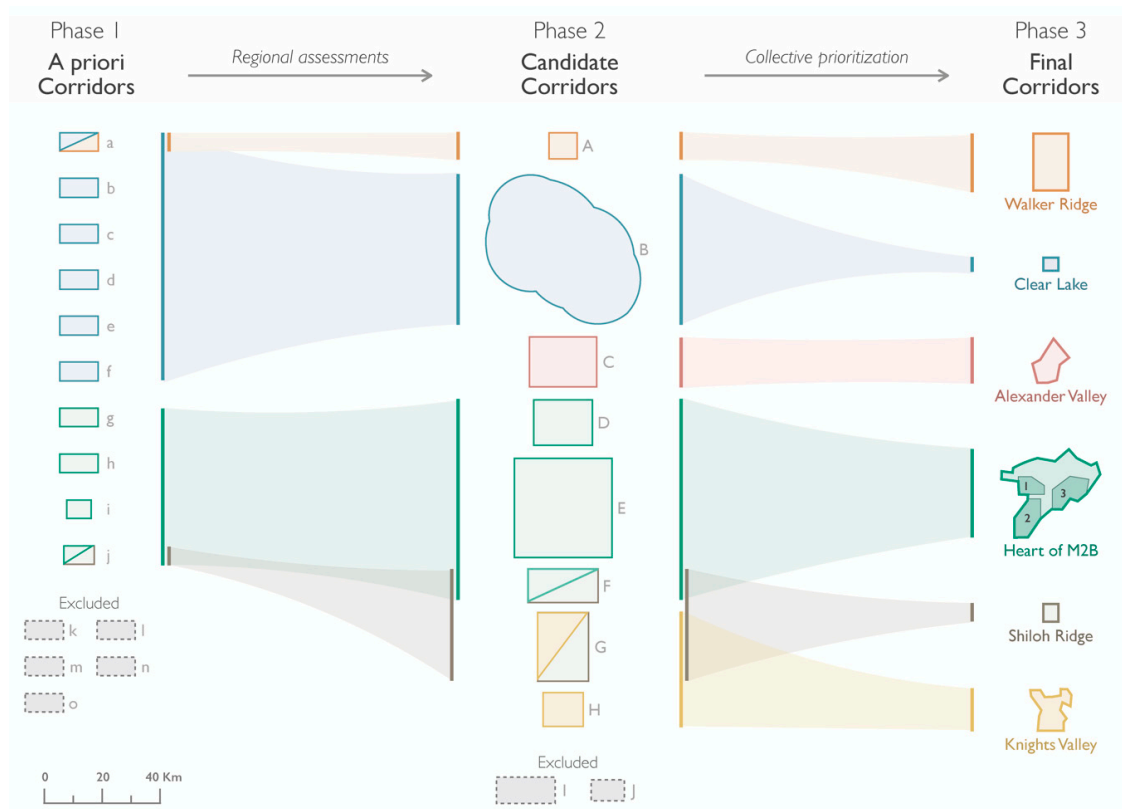


Figure 4. A flow diagram showing the relative size of focal areas identified as conservation priorities by stakeholders during the three phases of corridor prioritization with colors correspond to six final corridors; Walker Ridge (orange), Clear Lake (blue), Alexander Valley (red), Heart of M2B (green), Shiloh Ridge (brown), and Knights Valley (yellow); vertical bars capture the sets of focal areas that contributed to final corridors throughout the corridor prioritization process and corridors with two colors indicate the geographic extent was divided into two corridors at the subsequent prioritization phase.

Table 2. Table summarizing potential challenges that may be encountered when prioritizing corridors based on regional linkages created using a node-based approach. For each challenge, we provide a specific example and solution from the corridor prioritization process for the Mayacamas to Berryessa Connectivity Network.

Potential Challenge	Example	Our Approach
Methods used for the regional linkage assessment may be inadequate for identifying corridors at the parcel-scale.	Stakeholders identified a locally known habitat linkage that was not predicted by the regional linkage assessment. The threshold value used for the maximum number of connections per node in the regional linkage mapping was inadequate for a local-scale assessment when more than 3 protected areas are close together.	We conducted a second linkage assessment for the region of interest that used a larger threshold for the number of potential connections between nodes.
A parcel with high-quality habitat may have ownership and/or management practices that are incompatible with conservation goals.	Stakeholder knowledge of parcels with conservation-friendly landowners and/or used for higher-intensity agriculture or grazing within a potential corridor. Local parcel ownership and use unaccounted for in the input data used for the regional linkage assessment.	We revised the parcels included within the initial corridor boundary to (1) include those with permeable land and conservation-friendly landowners, and (2) exclude those with land use known to be incompatible with conservation goals.
Conducting a parcel-scale assessment for a large corridor composed of numerous potential linkages is computationally and technically demanding.	Stakeholders prioritized a large, county-spanning corridor (139.7 km ²) that spanned the Mayacamas and Vaca Mountains. Most of the land within the corridor had high permeability, and initially encompassed 53 least cost paths that connected 221 protected lands.	We developed a nested approach to prioritize the expanse of highly permeable land within the large corridor based on potential threat of land conversion. Regions with higher threat were designated as priority corridors and underwent a parcel-scale climate-wise connectivity assessment. Large swaths of undeveloped habitat (i.e., no agriculture, roads, or development) were designated as landscape linkages, and evaluated at a regional scale.
Standard node-based linkage assessment methods fail to account for the dominance of a single large node within a region.	Stakeholders sought to identify areas important for climate-wise connectivity within a single, large protected area with differing land management types. Protected lands with multiple management types may have highly variable interior permeability (e.g., within a single protected area some locations are managed for motorized recreation and others are designated for conservation).	We created a subset of nodes within a large protected area based on management type. The resulting nodes were used as input for a linkage assessment for the region of interest to generate potential linkages that were the basis for the final corridor.

Table 3. Table summarizing the focal areas identified as conservation priorities by stakeholders during a three-phase corridor prioritization process.

Corridor Type	A Priori Corridor	Candidate Corridor	Final Corridor
Prioritization Phase	Phase 1	Phase 2	Phase 3
Description	A region identified by an individual stakeholder at the project outset as a potentially important area for long-term connectivity and climate resilience.	A spatially explicit polygon delimiting a region prioritized by individual stakeholders for implementation.	A region of adjacent parcels collectively prioritized by the stakeholders and research team for climate corridor implementation.
Purpose	An initial inventory of local areas of a priori concern to stakeholders.	A subset of potential terrestrial linkages for consideration by the project team for parcel-scale corridor analysis.	Spatially explicit corridor extents for use in parcel-scale climate and connectivity assessments and summary reports.
When Delimited	At the project outset before the connectivity and climate assessments.	During 1:1 guided data exploration in which each stakeholder reviewed the connectivity and climate results with the research team.	Over a 9-month period using an iterative process to reach consensus among stakeholders.
Scale	Very coarse	Intermediate resolution	Parcel-scale
Size	Relatively small; narrow geographic extent	Larger than a priori corridors; wide geographic extent.	Similar in size to a priori corridors.
Area (km ²)			
Mean	81.9	530.9	38
Minimum	51.2	92.3	5
Maximum	92.3	2133.3	139.7
Range	41.1	2041	134.7

3.3. Cooling Benefits

Final corridors prioritized by stakeholders afforded an intermediate level of cooling benefit through terrestrial linkages. The mean cooling benefit afforded by terrestrial least cost paths (LCPs) within each corridor consistently increased with each iteration of corridor prioritization (i.e., from a priori, to candidate, to final corridor) for both summer and winter temperatures (Table 4). When compared with the a priori locations, the mean cooling benefit for LCPs in final corridors was 84% greater for summer and 92% greater for winter. An analysis of variance (ANOVA) was conducted for summer and winter temperatures to compare the cooling benefit of LCPs by corridor prioritization phase. We found a significant difference in cooling benefit by corridor phase for both summer ($F(2, 346) = 4.92, p = 0.01$) and winter ($F(2, 346) = 4.67, p = 0.01$) temperatures. A post hoc Tukey test showed the mean cooling benefit for LCPs in final corridors was significantly different from that of the a priori corridors for both summer (adjusted p -value = 0.02) and winter (adjusted p -value = 0.01) seasons. The cooling benefit of LCPs in final corridors did not significantly differ from that of candidate corridors for either season.

Stakeholders increasingly prioritized linkages with greater cooling benefit that were connected to partner properties throughout the corridor prioritization process. The percent of linkages in the 90th percentile (i.e., greatest cooling benefit) increased throughout the corridor prioritization phases for both summer and winter. The increase was greater for summer when compared to winter. Specifically, the percent of linkages providing the greatest cooling benefit was initially slightly lower for summer (summer = 6%; winter = 7%) and was ultimately greater by the final corridor phase (summer = 22%; winter = 16%).

Table 4. Table summarizing the cooling benefit for least cost paths based on their location (e.g., areas of initial concern, candidate corridors, final corridors). Temperature units are in °C.

Variable	Statistic	In Corridor			All Linkages	Not in Corridors	90th Percentile
		A priori Phase 1	Candidate Phase 2	Final Phase 3			
Least cost path (count)	Total	84	233	32	666	634	66
	Mean	6	36	5	—	—	—
	Minimum	0	1	1	—	—	—
	Maximum	19	96	13	—	—	—
Summer cooling benefit (°C)	Mean	0.99	1.47	1.80	1.13	1.09	4.12
	Minimum	0.00	0.00	0.00	0.00	0.00	2.90
	Maximum	6.92	6.94	6.92	7.00	7.00	7.00
	Range	6.92	6.94	6.92	7.00	7.00	4.10
Winter cooling benefit (°C)	Mean	0.53	0.71	1.02	0.68	0.66	3.17
	Minimum	0.00	0.00	0.01	0.00	0.00	1.55
	Maximum	3.37	3.37	4.91	9.29	9.29	9.29
	Range	3.37	3.37	4.90	9.29	9.29	7.74

3.4. Outputs to Support Corridor Implementation

Outcomes of the regional analyses included maps of linkage potential and climate metrics; summaries of landscape-scale trends; and the scientific context to help stakeholders successfully integrate the knowledge into ongoing conservation planning. The findings of the parcel-scale corridor analyses were summarized in six reports intended to provide stakeholders with site-specific data that may be used to assess priority locations for conservation and restoration. Each corridor report identified locations where connectivity or climate metrics were exceptionally high or low with geographic coordinates, and specified parcels with high values for both terrestrial and riparian connectivity (i.e., locations with connectivity co-benefits). Stakeholders co-authored content about factors relevant to implementation including a description of site-specific conservation benefits and the identification of critical land management partners, data gaps, and potential next steps.

All data, reports, and outreach materials were made publicly available on Data Basin and the data is included in the Biogeographic Information and Observation System (BIOS). Although data platforms are intended to promote accessibility, the level of stakeholder expertise with the interface can limit their ability to use the online material. Researchers and managers provided multiple training sessions to ensure stakeholders had sufficient technical knowledge to access, understand, and customize M2B data products on the platform. Initial training about the structure and use of Data Basin was provided to the M2B Network as a group. Detailed guidance was provided to smaller groups during working sessions as well as through a recorded live webinar.

One measure of success for collaborations between scientists and practitioners is whether stakeholders claim or accept partial ownership of final products [63]. The M2B Network created outreach materials shared as electronic resources, including a brochure for outreach to landowners, a two-page fact sheet, and a presentation that provided an overview of the M2B project and our research findings. The creation of the brochure involved defining the content and messaging at two in-person convenings and through online communication. Researchers and managers proposed content, and stakeholders provided feedback about concepts expected to resonate with landowners and highlighted potentially sensitive topics. Knowledge interplay between researchers and stakeholders was critical in the creation of the brochure. For example, some words and topics considered “scientifically neutral” by researchers were highlighted as having a second, potentially sensitive meaning by stakeholders, and were subsequently revised (or eliminated). The end result was a tri-fold letter-sized document with six panels on the front and back that provided a brief introduction to the M2B project, summarized corridors and their benefits, and identified seven ways landowners can keep their lands “wildlife friendly” (Supplementary Material, S3). Stakeholders demonstrated ownership of the final product by

independently printing the brochure and distributing it at their local offices and as a supplementary component of regular outreach materials mailed to their networks.

Outreach efforts build public support, which can be critical for the long-term success of conservation initiatives [64]. At the request of stakeholders, researchers and managers provided outreach presentations to partner organizations to share information about the M2B project and its findings. Longer-term education efforts included webinars and public presentations intended to provide education about the need for connectivity for climate resilience. While this project has focused on maintaining connectivity for wildlife movement, it is part of a larger conversation with decision-makers about the importance of connectivity for the health and livelihoods of people. For example, our communication materials emphasize how connected landscapes benefit people through the provision of essential ecosystem services. It is also particularly important for small urban centers—in Lake, Napa, Sonoma counties, and elsewhere—whose regional economies and livelihoods depend on viticulture, agriculture and forestry, all of which are tightly coupled to the environment.

The resulting high-resolution data products have already been used by stakeholders to inform conservation planning and to mobilize resources for conservation. For example, parcel-scale connectivity and climate estimates have been used by stakeholders to secure resources for climate-wise connectivity projects (e.g., Land Trust of Napa County, Lake County Land Trust), and the climate-wise connectivity assessment has been expanded to include all of Sonoma County to inform the county's "Vital Lands Initiative" intended to guide long-term acquisition priorities.

4. Discussion

Working together with the stakeholders resulted in added climate resilience as measured by the increase in the mean cooling benefit afforded by the final terrestrial linkages for both summer and winter temperatures. At the same time, the amount of land targeted for conservation narrowed through the prioritization process to the central project area between lands managed by the partner organizations, making implementation by the stakeholders feasible.

The outcomes of this project advance SDG 15 by providing the data needed for land managers to integrate ecosystem values and protected areas into planning and development processes to mitigate the impacts of climate change [1]. Stakeholders collectively prioritized the jurisdiction-spanning Heart of M2B corridor that encompassed lands managed by each partner organization. Ongoing collaboration among all stakeholders will be essential for future implementation. This type of multi-jurisdictional effort provides participant organizations with an opportunity to secure the resilience of lands beyond their individual management footprints, and approach that is needed to ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services called for under international agreements.

The findings demonstrate how stakeholders used co-produced knowledge in their evaluation of conservation priorities and how this process built the capacity of the M2B Network. The collaborative process described here resulted in changes in the geography of the final priority linkages and improved the climate resilience they are projected to provide the landscape in the future. Through regular and structured interactions among the network the stakeholders became familiar with the data, models, and the associated model uncertainty, which enhanced the credibility of the analysis and the perception that outcomes are based on legitimate and relevant information. In turn, researchers learned local information that was absent from spatial data. For example, opportunities for, and barriers to, implementation would not have been discovered without a collaborative exploration of the social and ecological context of the landscape. During the process of sharing information, additional data gaps were identified that need to be filled to improve future conservation efforts, including projected land use change modeling for the more remote lands within the project area that quantify threat [65].

Providing land managers with the tools to understand the climate connectivity value of a given parcel or region is only the first step. Communication tools and training help practitioners become more conversant about the importance of and rationale behind the science. The bridge between the regional

analyses and local action was the specific linkage reports developed to address site-specific habitat corridor projects prioritized by engaged conservation actors. M2B data products and supporting documentation provide a template for advancing regional and local conservation and serve as a resource for future climate-wise connectivity initiatives that can be further populated with fine-scale data queries and products to engage land managers and advance parcel-scale efforts. These tools may be critical in effectively engaging private landowners, who hold approximately 75% of undeveloped lands in the project area. This information provides the opportunity to target and evaluate specific acquisition or stewardship opportunities. It also provides a wealth of information to promote project implementation on the part of partners or investors, with a unique focus on climate adaptation value. Given that many funders are interested in investing in climate resilience, this information can raise the priority of identified corridors.

The peak of participant collaboration occurred during the six-month period when final corridor boundaries were delimited and analyzed on a parcel-by-parcel basis. M2B Network activity during this time was synergetic, with very high levels of communication occurring through corridor sub-committee meetings and iterative map development. Regular convening was essential to the formation of a coordinated social network capable of climate-wise connectivity implementation. It is critical to recognize that project teams and funders need to invest in the relatively high transaction costs that are involved in sustaining ongoing collaborations [59]. For example, the time and resources required by managers to plan, facilitate, and support the regular, in-person convenings of the M2B Network was substantial. Effective working relationships among members of the network was key and these relationships were formed through informal in person meetings and nature walks. However, remote interaction may be a viable alternative to in-person interactions later in the process for data sharing and exploration while maintaining effective knowledge co-production [66], and could reduce costs if working across large landscapes.

We recognize the challenges of measuring how social relationships advance (or hinder) the achievement of project outputs and outcomes. Because the feelings, emotions, and meaning-making processes of participants impact the inter- and intra-personal outcomes of a project [67], effective sustained engagement is integral to maintain the healthy interpersonal relationships needed to collaborative develop applied science [41]. An understanding of the influence of sustained interactions on the utility of co-produced knowledge may be obtained by documenting the variety of interactions between participants (e.g., [68]). Our project could have been improved by the inclusion of a more formalized evaluation design to document (1) factors (e.g., regional wildfires, institutional challenges, team-building activities) that impacted relationships and project outcomes, and (2) individual and institutional relationships over time (e.g., how they are built, maintained, strengthened, or lost) to better articulate the value of these underlying social components.

The approach presented here was intended as a collaboration among land managers with an in-depth knowledge of their local environment. Participating stakeholders hold knowledge of the diverse perspectives within local communities, such as those on residential, agricultural, tribal, and undeveloped lands.

Upon the completion of the connectivity analysis work described here, the stakeholders endorsed keeping the M2B Network active, and requested the inclusion of additional partner organizations (e.g., local agencies, tribes, non-profit organizations) to grow the network and increase its collective impact across a larger geographic area. Since then, the backbone organization has hosted a convening that included the M2B Network and their invitees to discuss shared approaches to advancing implementation strategies and securing funding. Emerging collaboration with landscape-level stewardship networks in neighboring counties opens the opportunity to use M2B methods to strengthen landscape connectivity throughout California.

5. Conclusions

This case study provides a framework for the co-production and use of credible and relevant climate-wise connectivity knowledge by a multi-jurisdictional conservation practitioner network. The outcome of this case study is six priority corridors agreed upon by the M2B Network based on spatially-explicit climate and connectivity data; local knowledge about resources and threats; and equitable representation across the partnering organizations. We found that iterative co-production shaped ecological objectives, input data, analytical methods, and implementation priorities; resulting in corridor priorities that afforded greater climate benefit and were more likely to connect lands managed by participant organizations. The study's history, lessons learned along the way, outcomes, and plans for the future provide insights to advance landscape scale resilience to climate change. In particular, facilitation by a backbone organization is key to create the enduring connections across landscapes and between individuals necessary for effective climate change adaptation. These findings illustrate the importance of partnerships between conservation scientists and practitioners working to bridge the gap between connectivity research and implementation.

Supplementary Materials: The following are available online at <http://www.mdpi.com/2073-445X/9/11/413/s1>, S1: Terminology developed and used by the Mayacamas to Berryessa Connectivity Network (M2B); S2: Mayacamas to Berryessa Connectivity Network (M2B) pre-project survey questions; S3: Mayacamas to Berryessa Connectivity Network (M2B) Outreach brochure for landowners.

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