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The benefits of big-team science for conservation: Lessons learned from trinational monarch butterfly collaborations

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Many pressing conservation issues are complex problems caused by multiple social and environmental drivers; their resolution is aided by interdisciplinary teams of scientists, decision makers, and stakeholders working together. In these situations, how do we generate science to effectively guide conservation (resource management and policy) decisions? This paper describes elements of successful big-team science in conservation, as well as shortcomings and lessons learned, based on our work with the monarch butterfly (*Danaus plexippus*) in North America. We summarize literature on effective science teams, extracting information about elements of success, effective implementation approaches, and barriers or pitfalls. We then describe recent and ongoing conservation science for the monarch butterfly in North America. We focus primarily on the activities of the Monarch Conservation Science Partnership–an international collaboration of interdisciplinary scientists, policy experts and natural resource managers spanning government, non-governmental and academic institutions—which developed science to inform imperilment status, recovery options, and monitoring strategies. We couch these science efforts in the adaptive management framework of Strategic Habitat Conservation, the business model for conservation employed by the US Fish and Wildlife Service to inform decision-making needs identified by stakeholders from Canada, the United States, and Mexico. We conclude with elements critical to effective big-team conservation science, discuss why science teams focused on applied conservation problems are unique relative to science teams focusing on traditional or theoretical research, and list benefits of big team science in conservation.

KEYWORDS
conservation delivery, *Danaus plexippus*, international conservation, science coproduction, strategic habitat conservation, team science

1 Introduction

"*Are some of science's most important questions simply unanswerable without redefining how research is done?*" (*sensu* Coles et al., 2022). We argue that for conservation science the answer is a resounding "yes," and an effective process increasingly involves working through a broad network of interdisciplinary decision makers, stakeholders, and scientists to coproduce actionable science designed to guide resource management and policy decisions. While many papers on the science of teams have been published, few case studies exist (Henson et al., 2020), especially for big teams working on conservation-oriented problems. As such, we describe a salient example of big-team conservation science focused on the monarch butterfly (*Danaus plexippus*), drawing from the literature of big-team science and our collective experiences, and offer recommendations for advancing big-team science approaches for solving some of the most important conservation problems.

We begin by summarizing published descriptions of effective science teams, highlighting the benefits of big-team science, elements of success, effective implementation approaches, and barriers or pitfalls. "Big-team science" has been described as a broad movement towards large-scale grass-roots science collaborations, self-organizing to align intellectual and technical capacity in pursuit of a common goal (Coles et al., 2022). Whereas traditional research teams tend to be smaller in scope, institutionally more isolated and competitive, big-team science is based on networks of collaborators coordinating across institutions—in our case, an international team aligned across federal and state agencies, non-governmental organizations, and academia. The size of these teams may be quite variable; what distinguishes "big-team" science is not necessarily the number of partners but rather the scope and scale of the problem, the dispersed and interdisciplinary nature of the participants, and a highly collaborative spirit driven by mutual interests and/or practical necessity.

The terminology used to describe or classify collaborative science endeavors varies by context, somewhat dependent on whether the framing centers on process, functions, structure, or outcomes. For example, Coles et al. (2022) distinguish "grassroots" big-teams from those developed with formal top-down funding (e.g., Human Genome Project). We view funding streams and the "top-down" vs. "bottom-up" organization of teams as a continuum of approaches to organize and fund big-team science. We recognize the overlap between conceptualizations of, and products stemming from, ideas called "big-team science" in conservation, "co-produced science," and "translational ecology" (Enquist et al., 2017) and intermix these terms when appropriate, but primarily we focus on team science, recognizing such teams will likely co-produce science and/or perform translational ecology when working on conservation problems.

We offer recent efforts for the monarch butterfly in North America as a proof of concept, an example of the effectiveness and challenges of applying big-team conservation science to a highly complex, and consequential, conservation problem. This narrative includes a description of the species' status and trend, the complex and diverse set of conservation actions and policies across Mexico, the United States, and Canada, the new conservation actions and policies that occurred in response to monarch declines, and the formation of the US-based and Trinational Monarch Conservation Science Partnerships (MCSP and Tri-MCSP) as team efforts for determining imperilment status and recovery options. We couch these science efforts in the framework of Strategic Habitat Conservation, the business model for conservation employed by the US Fish and Wildlife Service (USFWS) to meet conservation science goals identified by stakeholders from Canada, the United States, and Mexico.

2 Big-team science for conservation

The science of big-team science is an active area of discovery with recent work focusing on how interdisciplinary science teams function and can better deliver information that policymakers and stakeholders require. The primary benefit of big teams is their ability to solve difficult scientific problems emerging from complex systems, requiring diverse skills and perspectives and involving highly dynamic physical and/or political environments. Many conservation science problems meet these criteria, suggesting that conservation science (and desired conservation outcomes) may benefit greatly from big-team approaches.

Some of the reasons big-teams are well-suited to tackle complex problems include: 1) enhanced technical capacity for translational science (Vogel et al., 2014; Lotrecchiano et al., 2021), 2) leadership and coordination functions resulting in a holistic and strategic organizational alignment (Beier et al., 2017), 3) adaptive and interactive connections between researchers, managers, and applied policy decision-making contexts (Saunders et al., 2021; Chambers et al., 2022), 4) potential to leverage resources for added efficiencies and collective benefits, 5) momentum and positive feedback loops that may increase the relevance/utility of products and thereby the likelihood of diversified funding opportunities, 6) increased diversity, interdisciplinary or transdisciplinary thinking, and inclusivity among participants resulting in shared learning and novel ways of thinking (Vogel et al., 2014; Jagannathan et al., 2020).

However, not all conservation science problems demand big-teams. There is inherent power in such an approach, but there are also well-documented challenges accompanying large and dispersed science teams. The National Research Council book (National Research Council, 2015) remains an excellent distillation of the literature on team science, identifying 7 features of team science that can generate challenges and recommendations to overcome them. These features overlap with issues and challenges identified before (Pooley et al., 2014; Vogel et al., 2014) and after the NRC book (Baron et al., 2017; Saunders et al., 2021; Coles et al., 2022). Across these 5 studies, we classified the assorted challenges into 5 general themes: Funding, Team management, Team structure, Interdisciplinary effectiveness, and Credit/rewards (Figure 1).

These 5 themes cover a wide swath of issues affecting science teams. However, big-teams working on conservation-oriented problems have additional, perhaps unique, issues to consider. First, conservation or wildlife management science teams are, by design, formed to solve real-world problems. Given the urgency of the conservation mission, conservation science teams are often time limited, attempting to deliver science to meet a legal or politically

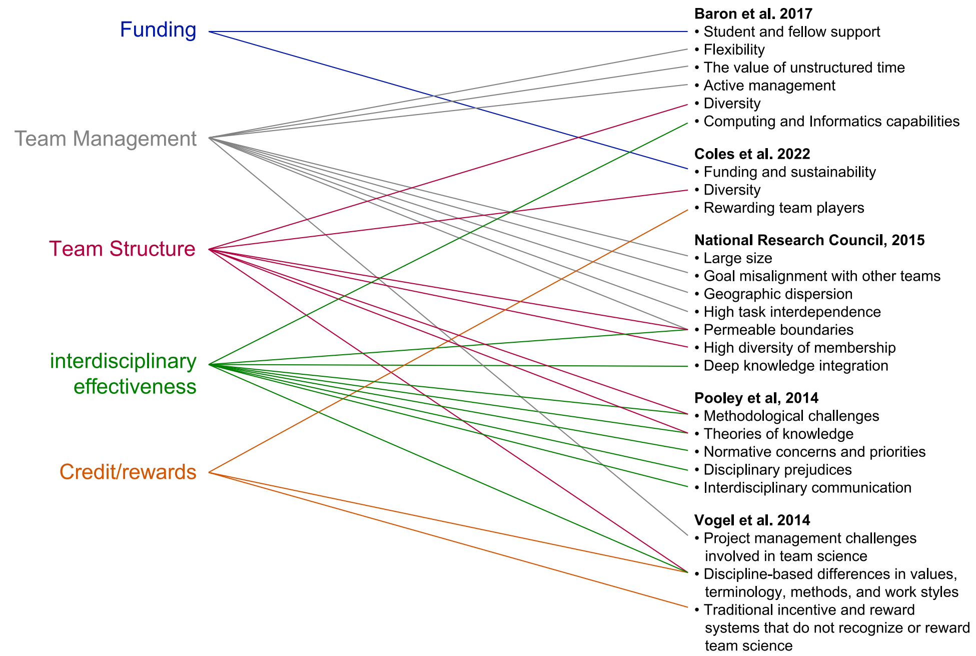

FIGURE 1
Five common challenges for science teams and the review papers that describe them.

determined timelines (Laurance et al., 2012). Whereas traditional research may rely on controlled or relatively stable experimental systems, conservation problems are inherently novel situations often associated with limited observational data and wickedly complex dynamic socio-ecological systems. Conservation science often happens simultaneously with large-scale planning, ongoing interventions, and environmental change. Furthermore, the conservation issue may be contentious, have numerous stakeholders with differing opinions, including legal actions, and these issues may affect the framing of the science that will or can be accomplished. Finally, conservation science teams may be organized such that scientists and non-scientists (stakeholders and decision makers) coproduce science by jointly framing research questions, the methods used to address them, and the interpretation of the results to inform natural resource management and environmental policy decision making (Beier et al., 2017; Saunders et al., 2021).

The monarch butterfly, as one of the most-studied insects in the world, offers an important case study in big-team conservation science. Whereas many conservation problems suffer from a dearth of information about extremely rare or obscure species, there are hundreds (if not thousands) of relevant publications focused on monarch biology and ecology spanning numerous decades. Thus, the challenge for monarch conservation is a matter of synthesis, new science directed at strategic gaps or sensitive assumptions, and adaptive application.

Decades of research completed since Dr. Fred Urquhart's announcement of the overwintering sites in Mexico (Urquhart, 1976) offers a foundational understanding of natural history, physiology, behavior, and other aspects of monarch biology. However, the conservation problem is a more recent phenomenon where population declines occur against a backdrop of unprecedented environmental conditions and a highly dynamic interplay between landcover and climate change, threats, and multiple conservation interventions across three countries. For many scientists the most important questions for monarch conservation science became: "What is the risk of extinction?," "what is an adequate population level?," "what are the threats and which ones can be/should be addressed?" and "how much conservation effort is enough?." These questions are inherently interdependent, informed (but not answered) by past research—indicating a prime situation where a big-team approach offers the necessary platform for multi-faceted integration. In sections 3–5 below, we provide an overview of monarch biology, recent declines, and the complex array of conservation actions to better frame the case study as an example of big-team science in conservation.

3 North American monarch butterfly biology and population trends

The multi-generational, multi-population continental-scale monarch migration phenomenon is extremely complex. In North America, monarch butterflies have two populations differentiated by the location of overwintering and breeding habitats (Figure 2). The much larger eastern population overwinters in oyamel fir (*Abies religiosa*) forests in the mountains of central Mexico, and migrates northward each spring, *via* 4 or 5 successive generations, from Texas and into the midwestern and eastern United States and Canada. The western population overwinters in forested groves along the California coast and northern Baja California, and moves north and east each spring, breeding throughout the region west of the

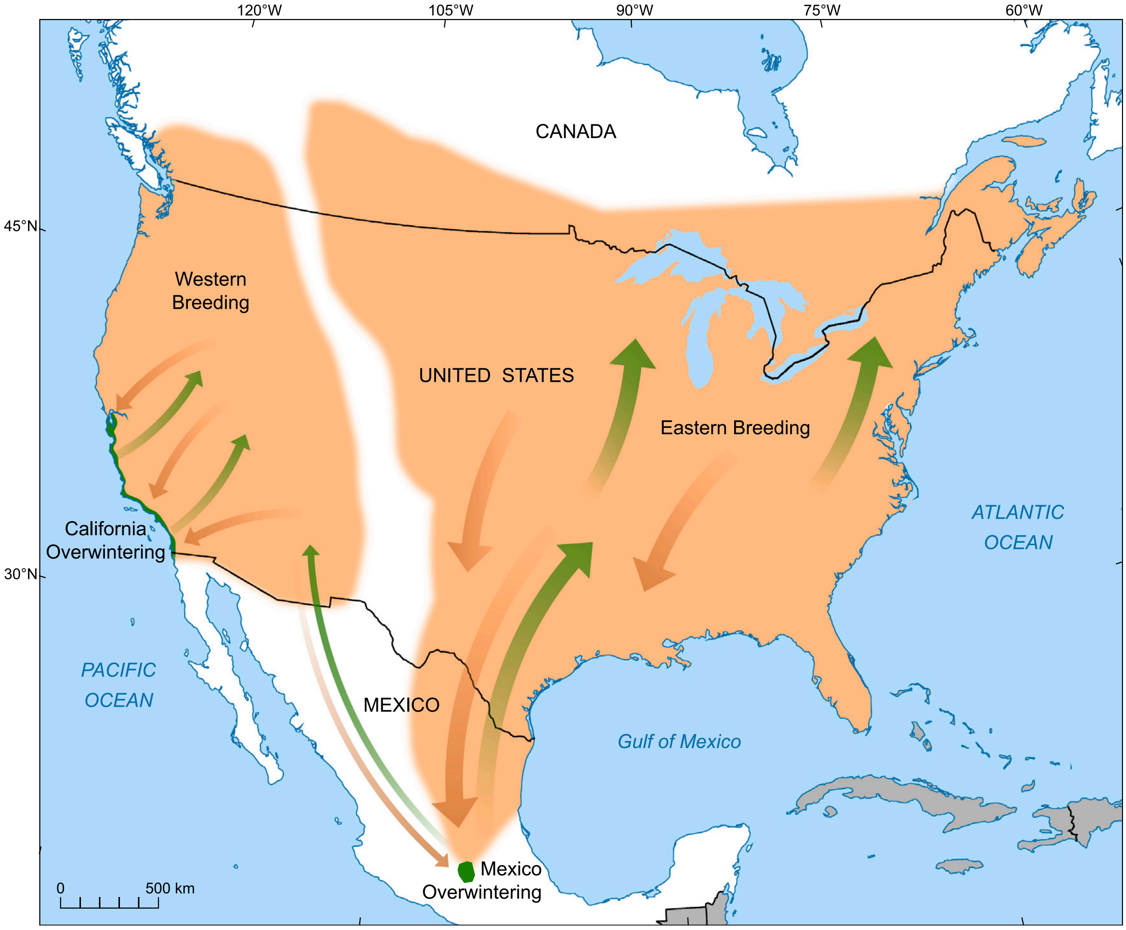

FIGURE 2
The generalized annual life cycle of monarch butterflies in North America. Dark green polygons represent areas of overwintering but the actual overwintering groves are much smaller. Green arrows represent spring migration, brown arrows represent fall migration.

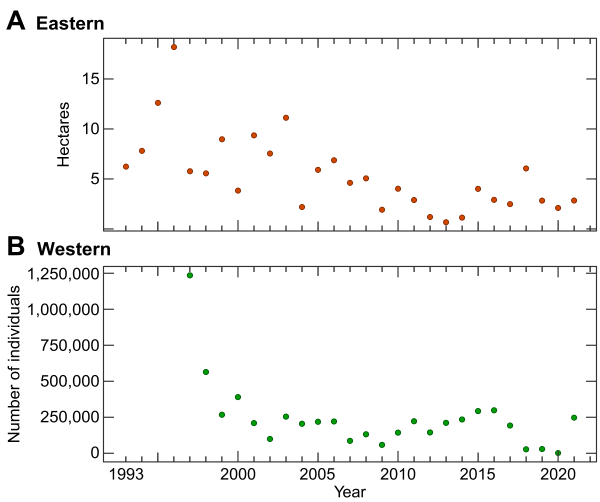

FIGURE 3
The number of hectares of overwintering habitat ((**A**), Eastern) and individuals ((**B**), Western) by year for the two monarch populations. Standardized monitoring of overwintering populations began in 1993 in Mexico (Rendón-Salinas et al., 2020) and 1997 in California (Xerces Society, 2022).

Rocky Mountains. These populations are not isolated genetically but show some phenotypic differences (Freedman et al., 2021). Tagged monarchs show animals in Arizona can migrate to either Mexico or California (Billings, 2019). After multiple generations of breeding and successive expansion from overwintering areas, environmental cues (Goehring and Oberhauser, 2002) result in reproductive diapause and the final generation of animals migrate south, returning to the overwintering locations. Monarchs lay eggs on a wide variety of milkweed species (genus *Asclepias*), which act as host plants for developing larvae. Adults require nectar from flowering plants during breeding and migration.

Both eastern and western monarch populations have declined in overwintering abundance (Figure 3). Area occupied by overwintering clusters in Mexico (Figure 3A) has varied considerably (Rendón-Salinas et al., 2020), but generally declined from the winter of 1996–97 to a low in 2013–2014 (Vidal and Rendón-Salinas, 2014; Semmens et al., 2016). The mean overwintering area from 1993 to 2008 was 7.6 ha, and from 2009 to 2021, 2.7 ha. In the West, sporadic sampling prior to 1997 suggests populations were highest in the mid-1980's at approximately 4.5 million butterflies and experienced a multiyear decline until 1994 (Schultz et al., 2017). Sampling by the Xerces society (Figure 3B) indicated populations peaked again in 1997 at approximately 1.2 million butterflies then declined to a relatively stable low from 1999 to 2017. In 2018, the population crashed to ~30,000 individuals (Pelton et al., 2019) and continued to decline until 2021, when it increased to ~200,000 individuals.

The causes of both annual variation and the longer-term declines have been extensively studied in both populations. For eastern monarchs, a leading hypothesis for long-term declines involves changing agricultural practices and associated landuse/landcover change, though other factors such as disease, predation, and toxicity from pesticides may play a roll. The adoption of genetically modified, herbicidally resistant corn and soybeans led to large losses of milkweed in agricultural fields (Pleasants and Oberhauser, 2013; Zaya et al., 2017) and is associated with declining population trends in Mexico (Thogmartin et al., 2017c; Saunders et al., 2018; Zylstra et al., 2021). This loss of milkweed could limit populations in more than one way–first, by reducing the total amount of breeding habitat and, second, by limiting the ability of females to find milkweed and lay eggs before they die (Zalucki et al., 2016; Crone and Schultz, 2022). In the west, habitat loss or degradation of overwintering areas and pesticide use in the California Central Valley has been associated with declines (Espeset et al., 2016; Crone et al., 2019; Pelton et al., 2019). Climate, primarily temperature and precipitation at various stages of the life cycle, has also been linked to annual population dynamics and to longer-term declines (Espeset et al., 2016; Zylstra et al., 2021). The loss of overwintering habitat remains a key threat for both western and eastern monarch populations. In Mexico, though forest loss has occurred (Vidal et al., 2014), Flores-Martínez et al. (2020) found that current rates of deforestation are low and that there is no evidence linking forest loss to eastern population declines since monitoring began in 1993–1994. In summary, with respect to monarch biology and population trends, the declining trends are well-documented but the cause-effect relationships associated with specific threats or drivers remain difficult to pinpoint due to limited data, correlated explanatory variables, and the observational nature of much of the data.

4 Monarch conservation status and protections

Numerous conservation efforts focused on monarchs exist across North America and were in place before data showing declines in the eastern and western wintering grounds were available. Shahani et al. (2015) provided detailed examples of these activities and organizations in all three countries. We provide an overview below, intended to convey the complexity and magnitude of conservation occurring across North America and the regulatory mechanisms engaged.

In Mexico, efforts to protect the fir forests where monarchs overwinter began in the 1980's based on the research initiated by Dr. Lincoln Brower, a founding proponent of monarchs and the conservation of their overwintering forests. Complex and difficult negotiations between World Wildlife Fund (WWF), landowners, and the federal government through the late 1990's resulted in the establishment of the Monarch Butterfly Biosphere Reserve (MBBR) in 2000. Economic incentives to landowners in the core zone of the MBBR who meet conservation commitments are facilitated by the Monarch Butterfly Fund (MBF, Fondo Mariposa Monarca; https://fmcn.org/es/proyectos/fondo-monarca; Honey-Rosés et al., 2009). In addition, the Alliance Initiative (https://www.wwf.org.mx/quienes_somos/nuestras_alianzas2/alianza_wwf_telcel/) provides financial support for overwintering population monitoring, environmental education, and reforestation (Semarnat y Conanp, 2018). Collectively, these programs have greatly reduced logging (Flores-Martínez et al., 2019; Flores-Martínez et al., 2020), and are a critical element of monarch conservation in North America.

In Canada, the monarch butterfly's breeding range extends across 10 provinces. At the federal level, the monarch butterfly is listed as a Species of Special Concern under Canada's Species at Risk Act (SARA) and is currently being considered for up-listing to Endangered. Legal protections under SARA usually only apply to federal lands. At the provincial level, monarchs are listed as Special Concern in Ontario and New Brunswick and Endangered in Nova Scotia under their respective species at risk legislations. However, only the latter listing affords the monarch protection by prohibiting killing, injuring, disturbing, taking or interfering with the species. Canada is actively working with the United States and Mexico to improve monitoring efforts in Canada using a trinationally adopted survey protocol (see Cariveau et al., 2019) through its main community science monitoring program Mission Monarch (www.mission-monarch.org).

In the United States, numerous monarch conservation (Shahani et al., 2015) and community science programs (Oberhauser et al., 2015) have protected and restored habitat and added to our knowledge of monarch breeding biology and migration over the last ~30 years. Projects such as Monarch Watch (www.monarchwatch.org), the Monarch Larva Monitoring Project (www.monarchnet.org/monarch-larva-monitoring-project), Journey North (journeynorth.org), and the Western Monarch

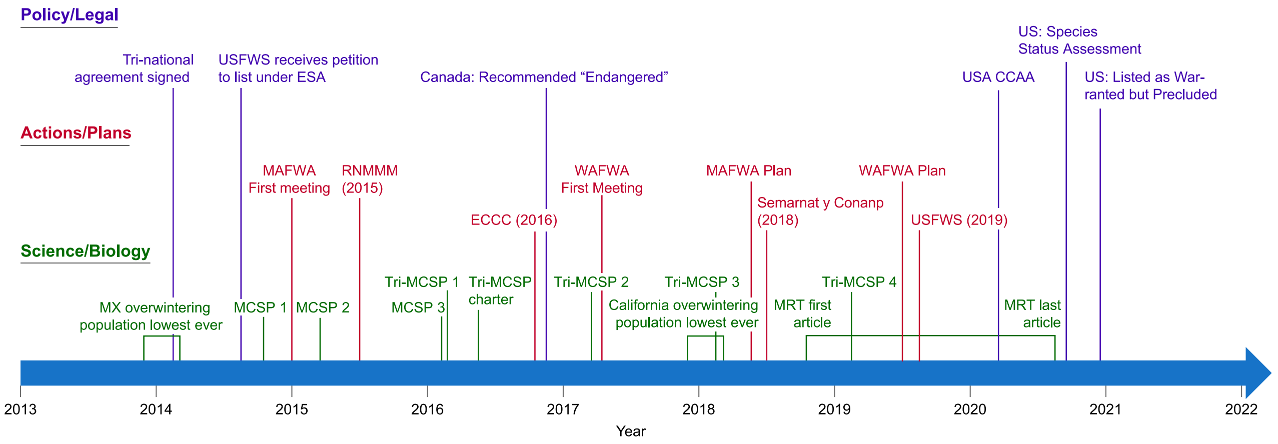

FIGURE 4
Monarch timeline showing policy activities, MCSP meetings, actions, and years of critical lows in populations size. Some actions and plans are labelled as they are cited and can be found in the literature cited. ECCC, Environment and Climate Change Canada; MAFWA, Midwest Association of Fish and Wildlife Agencies; RNMMM, Red Nacional de Monitoreo de la Mariposa Monarca en México; WAFWA, Western Association of Fish and Wildlife Agencies; MRT, Monarch Research Topic (Diffendorfer et al., 2020). The Monarch Joint Venture publishes an annual Monarch Conservation Plan (Monarch Joint Venture, 2021), which we did not include in the timeline. IMMP sampling began in 2016 and continues.

Count (westernmonarchcount.org) have been collecting data on monarchs since the late 1990’s. The multi-agency Monarch Joint Venture formed in 2008 and coordinates and implements education and conservation actions. In the western United States, protection and management of overwintering sites is a high priority (Pelton et al., 2016). The top 50 overwintering sites occur on both public and privately owned lands. Land ownership, in addition to state and local laws restricting development, creates different levels of protection across the sites.

International efforts to conserve monarchs include the North American Monarch Conservation Plan (NAMCP) (Oberhauser et al., 2008), developed after 3 international meetings of monarch biologists, NGOs, and decision makers in 2006 and 2007. The NAMCP outlined key trinational conservation objectives and outcomes to ensure that 1) sufficient overwintering habitat is available in Mexico and the United States; and 2) sufficient breeding and migrating habitat is available in Mexico, the United States, and Canada to maintain the overall North American population.

5 Response to declines

In response to the population declines described above, monarch conservation efforts have increased substantially. Viewed against a backdrop of habitat loss and a multitude of growing threats, these conservation efforts add another layer of dynamic complexity (and applied relevance) to the conservation problem.

Following two decades of observed population declines, eastern monarch overwintering levels in Mexico hit a historic low during the winter of 2013–2014 (Rendon-Salinas et al., 2020; Figure 3A). The alarming possibility of losing the migration phenomenon for the iconic monarch butterfly set into motion continental-scale efforts to mobilize conservation actions (Figure 4). At the North American Leaders Summit in Mexico, February 2014, Presidents of the US and MX and the Prime Minister of Canada responded with a shared commitment “to work on the preservation of the monarch butterfly as an emblematic species of North America which unites our three countries.” Prior to the meeting, the USFWS received a petition to list the monarch as a threatened species under the Endangered Species Act (US Fish and Wildlife Service, 2014).

The trinational agreement resulted in the development of multi-faceted federal policies and legal strategies across Mexico, Canada, and the United States. As part of these strategies, or in parallel, a wide network of partners rallied nationally and internationally to advance monarch conservation efforts. Mexico developed a comprehensive action plan for monarch butterflies aligned with trinational efforts (Semarnat y Conanp, 2018). In addition, WWF coordinated the formation of the Red Nacional de Monitoreo de la Mariposa Monarca en México (Working Group for the Conservation and Monitoring of the Monarch Butterfly Flyway), a forum for collaboration and coordination of efforts, capacities, and resources to conserve the Mexican flyway, which now includes over 43,000 butterfly sightings. In the United States, the USFWS began its species status assessment for monarchs (US Fish and Wildlife Service, 2020) and a landmark Candidate Conservation Agreement with Assurances (CCAA) for the Monarch Butterfly–the largest CCAA ever implemented–was signed (University of Illinois Chicago, 2020). Participating energy and transportation companies across the contiguous United States and authorities agreed to restore and maintain monarch-friendly habitat. Regional state-led monarch conservation plans were developed (Midwest Association of Fish Agencies, 2018; Western Association of Fish and Wildlife Agencies, 2019). In Canada, ECCC published a management plan for the monarch (Environment

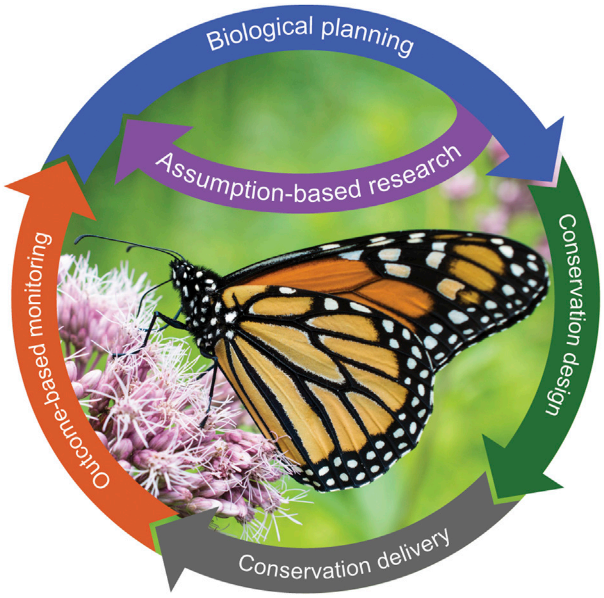

FIGURE 5
Elements of Strategic Habitat Conservation. SHC is an adaptive management framework developed by the USFWS. The MCSP primarily focused on Biological Planning, Conservation Design, and Outcome-based Monitoring. Monarch photograph by E. Weiser, USGS.

and Climate Change Canada, 2016) and as described above, the conservation status of monarchs was recommended to change from Special Concern to Endangered (COSEWIC, 2016) which is currently under review by ECCC. Since 2015, ECCC has funded over 108 projects related to monarchs and formed strategic partnerships to develop national level monitoring for milkweed and monarchs, to restore breeding and nectar habitat, and to develop a native seed strategy for restoration projects.

In 2022, the International Union for the Conservation of Nature (IUCN) evaluated and listed the North American monarch butterfly population as Endangered, indicating that the species faces a very high risk of extinction in the wild. While affording the monarch no legal protection in North America, the IUCN listing decision brings increased global attention to the eastern and western migratory monarch population declines and may serve as an additional catalyst for future conservation actions.

The response to monarch declines by the scientific community followed similar timelines, as an international scientific collaboration formed to help guide strategic conservation efforts and fill critical information gaps. A big-team approach emerged from a workshop in October 2014, where a group of conservation scientists initially focused on population modeling and geospatial priorities. This initial technical workshop coalesced a broader network of scientists from federal and state government, academia and non-governmental organizations, across Mexico, Canada, and the United States. This paper focuses on this extended group that would later be known as the "Trinational Monarch Conservation Science Partnership-Tri-MCSP", its evolution, structure and function, and how it coproduced science to meet information needs related to monarch conservation and management.

6 The monarch conservation science partnership

6.1 MCSP formation

The initial MCSP formally began in 2014 and met 3 times over the next 1.5 years at the U.S. Geological Survey's John Wesley Powell Center for Analysis and Synthesis. A previous USGS Powell Center working group on migratory species included monarchs as a case study and developed capacity within USGS in monarch butterfly ecology, initiated a scientific community of interest, and laid the foundation for a multi-organization working group.

As described above, science, monitoring, and conservation efforts for monarchs were in place well before the MCSP began. We designed meetings to include leading scientists, members of key NGOs, and active state and federal decision makers focusing on monarchs or monarch habitat. We emphasized participation from all 3 countries with scientists from Mexico involved through the entire process and Canadians joining from the second meeting onward. Bringing in those experts from North America who championed previous conservation efforts and performed much of the fundamental science on monarchs allowed the MCSP to build from their knowledge and existing data. Funding for the meetings came from the USFWS as well as Powell Center and the Ecosystems Mission Area at USGS. Some attendees covered their own travel expenses, which allowed additional participation.

The MCSP, by design, focused its scientific efforts on addressing information needs associated with Strategic Habitat Conservation (SHC) (National Ecological Assessment Team, 2006). SHC is an adaptive management framework the USFWS uses to plan and implement landscape-scale conservation. It is comprised of five elements (Figure 5): Biological planning, conservation design, conservation delivery, outcome-based monitoring, and assumption-based research to address uncertainties relating to each element (Thogmartin et al., 2011). The SHC framework was used to ensure a holistic, strategic, and adaptive approach to orient and coordinate our big-team science endeavors.

Extensive planning went into the first meeting (October, 2014). This included deciding who should, could, and were willing to participate, deciding on a main goal and potential objectives of the MCSP, and developing preliminary subgroup structure. The first meeting was structured around a list of potential objectives. By the end of the meeting, 6 objectives were developed and tied directly to the SHC framework and needs of international, federal, and state partners. For example, one initial objective was to "Identify knowledge and data gaps necessary to better conserve and manage monarchs." Discussion around this objective identified the need to set a target population size for overwintering monarchs as a conservation goal, estimate the amount of habitat required to meet that goal (i.e., biological planning in the context of SHC, Figure 5), and the need to garner a shared trilateral vision toward a science-based goal. Other specific objectives that arose during the first meeting were to determine habitat characteristics required to forestall further population declines through the exploration of restoration and

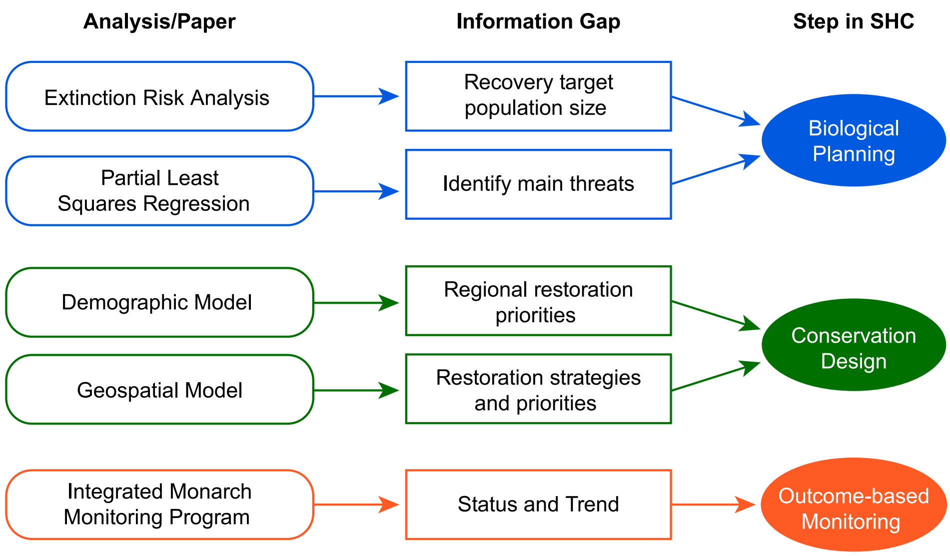

FIGURE 6
Analyses performed by the MCSP, the key information gap those analyses filled, and the associated step in SHC.

policy scenarios; identify the most critical locations for milkweed and nectar habitat restoration; develop a methodology to study and understand specific properties of habitat restoration actions that promote monarch production and can be tied to conservation targets; develop a plan for adaptively monitoring and managing restoration activities as they progress; and discuss the potential for citizen science engagement in restoration efforts. Given the need for a rapid response, the primary goal was the rapid development of a spatially explicit restoration plan that could be implemented over multiple years as funding and milkweed seed stock permitted.

Five months later, meeting 2 (March 2015) focused on completing the extinction risk analysis to inform the target population size in Mexico (Semmens et al., 2016), the spatially explicit matrix model to identify regional priorities for habitat restoration/conservation (Oberhauser et al., 2016), and geospatial analyses for prioritizing habitat restoration (Rohweder and Thogmartin, 2016; 2019). Other activities included an analysis of potential threats to monarchs (Thogmartin et al., 2017c) and discussions to develop what would become the Integrated Monarch Monitoring Program (IMMP) (Cariveau et al., 2019). Time was also spent coordinating science timelines with policy and decision-making processes involving USFWS, ECCC, states, and NGOs. The restoration priorities activity included splitting into two groups and estimating recovery potential of milkweed in different land-cover types. After values were solicited from each group, the entire MCSP discussed and agreed upon final values that were used in the prioritization analyses (Thogmartin et al., 2017b).

Meeting 3 (February, 2016) focused on completing the threats analysis, refining scenarios associated with the restoration priorities, the IMMP, geospatial data and tools, and addressing key data and management needs for the USFWS Species Status Assessment process. Work between meetings 2 and 3 related to restoration priorities suggested habitat targets could not be reached without important contributions from agricultural lands (Thogmartin et al., 2017b).

The 17-month timeline of work performed by the initial MCSP was designed to feed into the USFWS species status assessment of monarchs and the development of habitat targets and monitoring programs in Canada. In addition to the formal meetings, funding from the USGS Powell Center supported 1.5 post-doctoral researchers to perform work between meetings in collaboration with salaried scientists. Additional research developed in the MCSP continued after the last meeting, in particular the development and implementation of the IMMP (Cariveau et al., 2019; Weiser et al., 2021).

6.2 Evolution of the MCSP to meet international and Western United States needs

As the MCSP progressed, two key issues became apparent. First, coordination across countries was needed to better align political timelines relating to international aspects of the science produced by the MCSP. The majority of participants in the MCSP were simply not positioned to play this role. The Trinational Monarch Conservation Science Partnership had an initial meeting in February, 2016, 2 weeks after the final MCSP meeting, and was endorsed by the Trilateral Committee for Wildlife and Ecosystem Conservation and Management in May 2016. Led by the Comisión Nacional de Áreas Naturales Protegidas (CONANP), ECCC, and the USFWS, this international scientific collaboration met four times between 2016 and 2019 to tackle co-identified research priorities, promote applied science for strategic conservation, align monitoring efforts, and share data. Funding from the Commission for Environmental Cooperation (CEC) helped to catalyze these efforts by providing travel support to bring

TABLE 1 Key management reports, conservation plans, or monitoring programs (rows) and the MCSP science products they referenced (Columns). All items are listed as they are cited and can be found in the literature cited. COSEWIC = Committee on 222 the Status of Endangered Wildlife in Canada, ECCC = Environment and Climate Change Canada, MAFWA = Midwest Association of Fish and Wildlife Agencies, MJV = Monarch Joint Venture, WAFWA = Western Association of Fish and Wildlife Agencies, UIC = University of Illinois Chicago, IMMP = Integrated Monarch Monitoring Program. Note, the IMMP is a monitoring program, not a report.

Key monarch reports	MCSP science products									
	Semmens et al., (2016)	Thogmartin et al., (2017a)	Thogmartin et al., (2017b)	Oberhauser et al., (2008)	Thogmartin et al., (2017c)	Weiser et al., (2019a)	Weiser et al., (2019b)	Weiser et al., (2020)	Schultz et al., (2017)	Crone et al., (2019)
COSEWIC (2016)	X									
ECCC (2016) Semarnat y Conanp (2018)										
Midwest Association of Fish Agencies (2018)	X	X	X	X						
Western Association of Fish and Wildlife Agencies (2019)	X				X				X	X
Monarch Joint Venture (2019)	X	X	X	X	X				X	
US Fish and Wildlife Service (2019)			X	X					X	
UIC (2020)	X		X						X	
US Fish and Wildlife Service (2020)	X	X	X	X	X				X	X
IMMP						X	X	X		

representatives from the three countries together. The Tri-MCSP included some members of the MCSP, but also scientists, natural resource managers, and agency leaders from each country.

Second, some participants of the MCSP (C. Schultz and S. Black) were involved in western monarch conservation issues and encouraged a "westward" expansion of the MCSP to focus conservation and science issues unique to the western population. In 2016, a group of western monarch scientists, NGOs and decision makers met to prioritize science and conservation needs for the western monarch population. Like the initial MCSP meeting for eastern monarchs, the "Western Monarch Conservation Science Team" identified science priorities and conservation actions.

6.3 Tri-MCSP impact

Products from the initial MCSP and its international and westward evolution helped close key science gaps and inform steps in SHC. Much of the science produced was incorporated into key policy and conservation planning documents across all three countries (Figure 6; Table 1). For example, population viability analyses (Flockhart et al., 2015; Semmens et al., 2016), and estimates of overwintering densities (Thogmartin et al., 2017a) helped the three countries agree on a target population size for overwintering monarchs in Mexico (biological planning); spatially explicit population models (Flockhart et al., 2015; Oberhauser et al., 2016) and GIS-based scenario assessments helped inform conservation design (Thogmartin et al., 2017b); and the integrated monarch monitoring program was designed, evaluated, and implemented (Cariveau et al., 2019). In addition, members of the MCSP contributed to, and/or led, a 35-article, 150-author, research topic and e-book showcasing the current state of knowledge of monarch butterflies in North America (Diffendorfer et al., 2020). Articles in the e-book were published between October 2018 and August 2020, helping to inform the USFWS monarch species status assessment (US Fish and Wildlife Service, 2020).

6.4 What we missed

The most pressing questions facing decision makers (including those funding the MCSP) focused on population declines, their causes, and identifying restoration targets. These issues primarily required expertise in population ecology and took priority. To this end, the Tri-MCSP produced actionable science that helped guide monarch conservation, however it did not have an unlimited budget nor time to address all of the identified priority research. Other priority science topics we did not cover included genetics, pesticide impacts, and the role of nectar resources. In addition, there are many social and economic issues associated with monarch conservation problems/solutions and including such expertise would have allowed formal framing and investigations of these issues. As an example, the MCSP identified the need for conservation in agricultural landscapes (Thogmartin et al., 2017b) but did not have participants with knowledge about the agricultural industry allowing us to consider specific strategies affecting farming practices or broader agricultural policies, such as those reflected in the Farm Bill in the United States. Thus, while we made progress on the most pressing issues, our scope of work was more limited than what it could have been. Though the MCSP developed strategies for allocating conservation and restoration activities in breeding areas, we also could have allocated time to designing finer resolution spatial prioritization strategies and identifying information gaps needed to refine such strategies; such work was picked up to some extent, by step-down activities by the Mid-west Association of Fish and Wildlife Agencies Mid-American Monarch Strategy (2018).

7 Elements of effective conservation science teams

In this section, we reflect on the MCSP relative to existing literature on science teams. We describe the 5 general elements we derived from literature (Figure 1) relative to the Tri-MCSP and give associated recommendations.

7.1 Funding can be a limiting factor, but big-teams can also secure or create unique funding streams

In their review, Coles et al. (2022) suggested funding was a limiting factor in team science, and Pooley et al. (2014) mentioned how the structure of funding and priorities of funding agencies may limit multidisciplinary teams in conservation. There can be little doubt conservation science teams require funding. The MCSP was fortunate to work on a charismatic species that engendered support from national leaders. But even in our case, funding was a fickle beast. Federal funding for additional science workshops became very limited after the initial 2014–2016 MCSP activities. However, conservation teams, *via* their activities, can raise awareness for a species and generate momentum that can initiate new funding and conservation activities as well as additional science. This momentum generation was true for the MCSP. For example, USFWS and USGS funding supported the initial workshops and provided technical and coordination capacity, including a dedicated post-doctoral researcher, numerous research projects, and coordination capacity for state-led planning efforts. Building on the demonstrated utility of the initial MCSP science (e.g., population viability and threats assessments) for the Eastern monarch population, new opportunities emerged to secure additional funding streams. The US Department of Defense supported parallel threat assessment efforts applicable to Western Monarchs. The CEC supported the Tri-MCSP and provided funding to advance shared science priorities and data management needs. Different sectors of society also contributed in integral ways to develop a consistent approach for analysis and tracking of conservation efforts, as demonstrated by the alignment between the USFWS-developed Monarch Conservation Database, the state-led planning efforts, and the CCAA. Our experience suggests initial funding is likely required to start conservation-focused big science teams, but their unique collaborative structure and the inclusion of stakeholders, decision makers, and even potential funding entities, can generate new opportunities.

7.2 Consistent (and collaborative) leadership is critical

Big science teams need leaders who can effectively manage the complexities of the project. The MCSP was co-led by a Steering Committee of USFWS, USGS, Monarch Joint Venture (MJV), and Association of Fish and Wildlife Agencies (AFWA), while the Tri-MCSP was led by overlapping representatives from FWS, ECCC, and CONANP. These committees did much more than just organize meetings. Because they included representatives from key groups (scientists, managers, and stakeholders from each country), they were the primary nexus where co-production and translational ecology took place. Representatives acted as translators between the MCSPs and their organizations, helping to refine the work performed, and how that science was incorporated into decision making. In the MCSP and Tri-MCSP, translators were key in making the coproduction of science happen and these translators became leaders precisely because they could bridge science, policy-based decision making, and implementation. As noted in 7.3.1, a substantial portion of the team may converge around a new problem, or disperse when a project is completed, but a consistent lineage of leadership is important to guide the overall effort, secure necessary resources, and ensure connectedness/relevance.

7.2.1 Peer-reviewed science needs to begin long before decision-making deadlines

Effective conservation and restoration often require timely decision-making and/or policy determination (Martin et al., 2012). There is often a multi-year window during regulatory processes that will utilize scientific inputs, ideally in the form of peer-reviewed publications or tools. Therefore, the timeline for science delivery must acknowledge and be pertinent to the deadlines for decision making, requiring a proactive approach to advance the state of the science in anticipation of the needs of decision makers. Synchronizing these two timelines, decision-making/politics and science delivery, takes constant work and continual adjustment. It is an adaptive process, where adjustments are made in 'real time' to both timelines. In the case of monarchs, both the United States and Canada had timelines associated with the legal status of monarchs. The Tri-MCSP used these decision-making timelines to prioritize and order scientific products. Individuals representing the federal agencies making policy decisions for Canada and the United States were also Tri-MCSP participants, a key connection allowing tight integration between the two timelines.

7.2.2 Science-policy translators play a key role in applied conservation science

Young et al. (2014) describe the need for 'translators' who bridge science and policy and maintain high levels of communication within a team. We did not identify translators during our initial scientific scoping, but both the MCSP and Tri-MCSP had translators who effectively communicated within, between, and outside of these groups. Translators were deployed by the leading federal agencies as the scientific and policy needs became clear. Early efforts from MCSP, resulting in the population viability analysis for the eastern population, opportunistically served as a proof of concept. For example, co-authors RGD, GM, and IMM were critical to aligning the science products from the MCSP with the United States, Canada, and Mexico species status assessments and conservation planning processes. RGD also bridged communication gaps as the MCSP evolved into the Tri-MCSP, which helped the MCSP hone science to best meet international concerns, and then translate that science back to higher level decision makers. Other members of the MCSP, given their leadership roles in NGOs and other agencies, were able to translate science from the MCSP directly to conservation and management actions for monarchs. We concur with Young et al. (2014) about the need for translators to play a strong, regular role in the management and operations of applied science teams and encourage thoughtful identification of them while planning. Tapping into existing conservation networks is a good way to engage effective translators.

7.2.3 Bringing people together is very effective

Particularly when working across disciplinary, geographic, and/or bureaucratic boundaries, it is critical to bring people together. The rise of virtual meetings may help to alleviate some former barriers, but there is no true substitute for workshop-like settings to drive collaborations. Focused time to brainstorm together, to build bonds among collaborators, and to encourage interdisciplinary thinking was extremely important for these efforts. In several instances, substantial scientific publications resulted from minimal funding where the primary contribution was supporting travel and allowing for focused time to formulate ideas, plan the analyses, and clarify roles and responsibilities to complete the work. Small investments to fund travel and support workshop-style meetings can pay big returns in terms of scientific accomplishments.

We are convinced of the critical role funding plays in bringing people together. The majority of MCSP funding paid for travel and meetings at the USGS Powell Center. Trinational travel support provided by the CEC was also critical. The ability to meet in-person, at a science-synthesis center, established critical trust among participants and allowed personal connections to develop among participants. This trust is important in long-term science collaborations, and critical for big-team science. Many of the resulting publications stemmed from the highly collaborative workshop environment of the in-person meetings. For these reasons, funding to support travel was as important as funding to do the technical work.

7.3 Team structure matches the applied nature of the conservation problem

Conservation and restoration-oriented teams are not the same as teams generating basic science and this difference influences recommendations for how conservation science teams should be structured. Including a mix of scientists, managers, and policy experts allows teams to integrate science, decision making, and management implementation. To do so effectively, they can include a mix of scientific disciplinary experts, stakeholders, decision makers in positions of power, and individuals who can implement conservation actions in the field or access citizen networks, or extension networks that provide outreach and education. In some cases, every player cannot fit in the room, people cannot participate for personal/professional reasons, and team structure may be affected by levels of funding and the timing necessary to deliver science into the hands of decision makers/stakeholders. However, developing an effective conservation science team must deliberatively identify and gather those individuals who collectively generate the needed mix of skills and positions of power (Irwin et al., 2011) to solve the conservation problem.

7.3.1 Teams may evolve as the problem (and process) evolves

Many conservation problems, particularly those associated with migratory species, span large geographic regions and cross international borders. Furthermore, governments and decision-making bodies are hierarchically organized. To best handle monarch conservation across North America, we included a high level of flexibility in the original MCSP, bringing different experts or decision makers to best match the goals of each meeting (O'Donnell et al., 2017). For example, of the 45 people who attended the 3 MCSP meetings, only 14 attended all 3, 6 attended 2, and 25 (55%) attended just 1. The "singletons" played critical roles in both adding expertise during science discussions and framing (for example, restoration scenarios), and acting as translators - taking information from the MCSP back to other monarch conservation efforts such as the USFWS species status assessment (SSA) process; country, regional, and state habitat conservation planning; and the CCAA process. In addition, as the need for both international and westward expansion of the MCSP model became apparent, original members of the MCSP helped develop and were involved in these new efforts. Not all conservation science teams will require these types or levels of flexibility, but leaders may prepare to be flexible. A subset of participants on big teams will inevitably change. Some participants drop out for either personal or professional reasons, key members cannot attend a meeting, and changes in higher-level politics (such as elections) may alter support for specific science efforts. Components of these efforts can be modular and ephemeral by design, organized around focal topics/publications or phases (sprints) within the longer-term arc of the science. Ultimately, leaders should consider structuring teams, individual meetings, and longer-term plans to best deliver effective conservation for the species.

7.4 Teams will enhance interdisciplinary effectiveness

Given their structure, conservation science teams will nearly always include individuals from different academic disciplines, careers, and regulatory agencies. How do we make teams of scientists, wildlife managers, conservation leaders, and regional or national policy leaders effective?

7.4.1 Big-teams can help to promote collaborative science over competitive science

Whereas traditional research often occurs in relatively isolated lab groups, competing for funding and prestige, big-team conservation science requires high levels of co-produced, collaborative science for effectively informing conservation decisions (Saunders et al., 2021). These collaborations can take many forms. At very personal levels, this collaboration may mean, for instance, a scientist subordinating their professional goals for group goals deemed higher priority. It can also mean cross-agency and cross-country coordination in funding directed towards those best equipped to deliver the necessary scientific insights at the speed needed to inform quickly developing conservation decisions. This type of coordination is very different from the typical competitive funding model (Fang and Casadevall, 2015) and, indeed, there may be no open calls for research proposals at all. As described above, the collaborative approach can result in the generation of novel funding streams and team-based momentum that can result in prolific opportunities for co-authorship across all career phases. To best inform conservation, collaboration also means ascribing to open science principles, so data, code, and workflows are shared as insights are identified. Finally, we suggest a key element of collaboration in science-conservation partnerships is understanding the needs and expectations of participants and attempting to structure outcomes to best match the interests, skills, and ambitions of the team.

7.4.2 Coproduction of conservation science helps to answer the most important policy questions

Young et al. (2014) discuss the need to frame research and policy jointly. This recommendation is dependent on the legal and social contexts of decision making and the scales at which conservation will be implemented. In our case, broad-scale policy was already in place: high-level communication among the leaders of each country had prioritized monarch conservation; the monarch was under consideration for listing in the United States and Canada, and all three countries, and regions/states within them, already had a wide variety of conservation programs in place for monarchs. The managers and NGO participants of the MCSP were astute in understanding this "decision space" and helped frame the most relevant scientific questions. Given this background, we began by anticipating the science required to fill information gaps associated with existing policy, then embarked into a highly dynamic space where science translators worked to drive an adaptive process to coproduce science. The existing policy helped scientists prioritize the core research questions, but the presence of existing policy needs may not always be the case. For example, the United States Senator from Oregon, Senator Merkley, recently hosted a western monarch summit (Merkley, 2022). Here, the reverse took place. Science gaps and conservation needs of the western monarch population formed the basis for policy recommendations that could be worked on by the United States Congress, government agencies, and a broad array of other partners.

7.4.3 Big-teams must break down complexity into solvable parts and work *via* parallel sub-teams

Breaking down multidisciplinary conservation problems into solvable but integrated parts allows greater focus. On its face, conserving a species that has multiple generations a year, migrates across 3 countries, and has different socio-ecological systems driving unique threats (and potential solutions) across its range, seems like a classic "wicked problem" (Horst and Weber, 1973). Trying to tackle the entire scope of work cannot, and we argue should not, be done with a single conservation science team. We approached the problem in a holistic way and advanced the science in key areas–population viability, threats, conservation targets, and monitoring, alongside an adaptive management strategy. Each effort could potentially stand alone, but collectively they were much more meaningful for informing decision making.

The MCSP used SHC to frame our approach and it worked well. SHC, by organizing species conservation into sequential steps, both identified information gaps needed for particularly important management questions (such as, what is the target population size for recovery?) and focused the science to address these questions. Using SHC allowed the MCSP to focus on the population ecology of monarchs, the breeding habitats required to meet recovery targets, and monitoring design and implementation. We note that SHC is one of many ways to frame conservation for species. Structured decision making, expert elicitation, or other approaches could have been used to identify key focal issues. Regardless of the approach, jointly identifying key decision making and management goals is a critical first step to identifying science gaps.

7.4.4 Bigger teams and/or broader multi-disciplinary scope is not always better

Team size and interdisciplinary breath reflects the scope of the problem. The natural sciences cannot alone solve the complex conservation problems facing society (Mascia et al., 2003; Chan et al., 2007; Schultz, 2011; Hicks et al., 2016). Despite these calls, and the real need, for more multidisciplinary efforts, effective conservation science teams may not need a wide swath of disciplines to solve the most pressing conservation science questions. The MCSP included monarch biologists, population ecologists, and plant ecologists as science disciplines, alongside conservation leaders from NGOs and state and federal managers. The key SHC-related science gaps the MCSP tackled did not, for example, require social scientists, though monarch conservation has a large social component. As mentioned in 6.4, with more funding and perhaps more time, the MCSP could have incorporated social science and agriculture interests while studying the need to increase pollinator habitat in agroecosystems, understanding farmer needs, their support for monarchs, and the economic burdens they may face if asked to create or restore pollinator habitat on their lands. The MCSP had relatively low disciplinary breadth across the sciences but had a much broader swath of policy and natural resource management decision makers and stakeholders who spanned countries and multiple levels of governance, from local, to state, to federal government agencies. Ultimately, the scope and breadth of a conservation-oriented science team is best driven by complexity of the conservation problem being addressed.

7.4.5 International science collaborations are not easy

The MCSP generated sufficient science to establish trinational agreements on a target population size and bring international scientists together to discuss gaps in our understanding of monarchs. However, none of the core science products from the MCSP were utilized in Mexico's or Canada's monarch conservation plans (Table 1). This result may not be problematic: each country has unique conservation goals, science needs, policies, and institutional structures for implementing conservation. In the case of Canada, demographic modelling by Canadian scientists prior to the MCSP (Flockhart et al., 2015) was used in their conservation plans. In Mexico, the science necessary to conserve overwintering groves and migratory habitat are largely independent of similar needs in the United States and Canada. The Tri-MCSP agreed on 7 science priorities: 1) natal origins of migrating butterflies, 2) estimating overwintering density, 3) climate change impacts, 4) pesticides, 5) understanding and mapping nectar resources across North America, 6) data sharing/data management, 7) full-annual-cycle monitoring. A few of these are moving forward but organizing and implementing continent-wide research that can drive national conservation strategies remains very difficult for many reasons, including but not limited to communication challenges, funding limitations, logistical issues, and political challenges.

7.5 Cleary defined credits and rewards help the team function

Scientists, particularly those in academic research, are under pressure to publish papers and generate research funding. The rewards stemming from conservation teams may not align with the reward systems academic (and some federal) scientists operate under, particularly those valuing first-authored papers over participation and leadership of science teams. Cooke et al. (2020) offered a number of contribution criteria, that if adopted and used in the evaluation of scientists, could better align team science participation with career rewards. While we wait for academic reward systems to catch up to real world needs, what can conservation science teams do to attract and reward scientists? In the MCSP, the majority of participating monarch scientists were well-established in their careers, highly committed to monarch conservation, and voiced few concerns about issues such as authorship. This arrangement is one obvious strategy, though it is likely not realistic for many teams. Being upfront about commitments, rewards, and limitations, then being flexible about who can participate, how much they can and will participate, and who will lead the science products are essential issues to resolve early in the conservation partnership. Another approach the MCSP took was simpler and straightforward. The priority was getting science done to address monarch conservation. Those scientists with the availability and expertise to lead these efforts within the decision-making timeline did so; others volunteered to contribute where interests and capacity aligned. In this line of thinking, the conservation science and species came first, while parity across science team participants played a secondary role. PIs from the MCSP were able to mitigate this to some extent by nominating the body of work for team awards.

7.6 Successful teams communicate

Effective communication is fundamental to several the elements listed above and critical for teams that function at high levels. Communication happens in many forms and in the case of the MCSP was generally between team members, between the team and decision makers, and between the team and the public. The in-person meetings at the USGS Powell Center allowed deep communication and built trust. Regularly scheduled video-conferences maintained communication between the meetings. A key motivation for the Tri-MCSP was explicitly to foster better communications between countries and bring ideas back to scientists in the MCSP. Communication from the MCSP to the general public was primarily handled by the well-established public outreach from participating NGOs like Xerces, Monarch Watch, and Journey North.

8 Conclusion

Why are big science teams beneficial to conservation? While reading the literature about big-team science we were surprised by the lack of papers focusing on benefits. Many papers never mentioned benefits and focused solely on challenges. To this end, we felt a list of benefits would contribute to the broader understanding of why big-team science in conservation can be useful and adopted and supported when possible. As noted by Beier et al. (2017) our brief bullets "gloss over many of the complexities." The following benefits stem from both literature (a citation is provided) and our experience with the MCSP.

Big-team science in conservation. . .

- Increases the ability to tackle complex, long-term conservation challenges, including those that entail landscape change and dynamic environmental conditions across international borders.
- Promotes a holistic and more integrated approach (*versus* an assemblage of independent research projects).
- Bridges the research-implementation gap (Saunders et al., 2021).
- Enhances coordination between science and management decision timelines.
- Can rapidly fill information gaps critical for conservation decision making.
- Hones and prioritizes potential science activities so the work that most addresses management issues is done first.
- Breaks up the work across multiple scientists, speeding up the rate of science production; this can lead to a prolific portfolio of work that is further strengthened by numerous phases of peer-review.
- Provides more technical capacity to perform the work (Vogel et al., 2014; Lotrecchiano et al., 2021).
- Increases diversity and inclusion resulting in shared learning and novel ideas (Vogel et al., 2014; Jagannathan et al., 2020; Chambers et al., 2022).

- Offers unique opportunities for early-career scientists to contribute to or lead high-profile publications alongside established leaders in the field(s).
- Generates more creative ideas because stakeholders, decision makers and scientists, share information.
- Creates opportunities for collaborative, open, data sharing and synthesis.
- Produces a longer lasting community of practice around the current conservation issue, but also future conservation issues; The community includes scientists, decision makers and conservation practitioners who are ready to work together again if the need arises.
- Provides constant learning opportunities with respect to science, policy, and social contexts as well as broadens perspective.
- Results in increased personal motivation and inspiration.
- Generates momentum which can lead to more funding and additional science.
- Helps leverage funding.
- Improves efficiency by making sure efforts are not duplicated.

Given the current pace of changes to the environment and coincident declines in biodiversity, there is a strong need for both more big-team science in conservation and examples of what makes conservation science teams effective. In our collective experiences, we have routinely seen scientists engage with decision makers and groups performing restoration and management, have participated in such groups, and noted varying levels of success. We were motivated to develop this paper because the MCSP was successful–and because these successes can likely be replicated to tackle other conservation science problems. Key takeaways from our experience suggest big-teams in conservation science must be funded, structured and managed to deliver actionable science for decision makers. This applied focus permeates decisions regarding team structure and leadership, prioritizes the order science products are delivered to meet decision making timelines, and requires intimate coproduction of science. Furthermore, effective conservation science teams require individuals who act as translators, facilitating two-way communication between scientists and policy makers and/or individuals who implement management activities. With technology allowing us to enter a new paradigm of science characterized by large amounts of open access data and synthesis (Hey et al., 2009), big-team science is more viable than ever, and as our case study shows, has high potential to solve conservation problems. Big-team science may become increasingly necessary to tackle the complex conservation challenges of the future.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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