The unrealized potential of community science to support research on the resilience of protected areas

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Abstract
To remain effective into the future, protected areas must be resilient to change. Evaluating the resilience of protected areas requires data across large spatial and temporal scales, which has proven to be a strength of community science in conservation research. Here, we assess the contributions of community science to different topics of protected area research and identify gaps where community science can be used more effectively. We performed a literature search aimed at capturing the research on resilient protected area design and management, then used Latent Dirichlet Allocation to model the topics represented in this corpus. Once topics were established, we searched for evidence of community science being used in each publication. Our analysis showed that there are five main areas of focus in resilient protected area research: biodiversity, climate change, connectivity, resources and ecosystem services, and social governance. We found limited evidence in the literature of community science directly assisting research in these areas. Community science has proven effective for extensive and cost-effective data collection in other situations; therefore, we recommend ways in which conservation managers and researchers can incorporate community science in the design and management of resilient protected areas.

KEYWORDS
biodiversity, citizen science, climate change, connectivity, conservation, ecosystem services, reserve design, resilience, resource management, social–ecological systems

1 | INTRODUCTION
Protected areas, which are spaces that are clearly defined, recognized and managed to protect nature through legal or other effective means (IUCN, 2008), can serve many objectives, including the conservation of natural resources, the maintenance of ecosystem services, and the preservation of heritage sites (Gladstone, 2009). Protected areas are also a nature-based solution to climate change (Nesshöver et al., 2017). However, serving those objectives effectively over the long-term requires that they be resilient to change. In general, resilience can be defined as the ability of a system to adapt to internal
changes and external disturbances to maintain its objectives (Cumming et al., 2005). The complexities of natural systems and the varying objectives of protected areas can make what contributes to resilience unique to an area and therefore difficult to measure in a standardized way. For our purposes, we define resilience as the capacity of a protected area to retain its essential functions over time, whether those functions are preserving biodiversity, providing ecosystem services, or any other objectives. Assessing resilience effectively typically requires data collected at greater spatial and temporal scales than conventional methods can provide (Cushman & McGarigal, 2019).

One potentially important method of informing conservation decisions is through community science: the public participation and collaboration in monitoring and research, often motivated by the desire to advance scientific knowledge or contribute to conservation decisions (Tulloch, Possingham, Joseph, Szabo, & Martin, 2013). Community scientists (also commonly referred to as citizen scientists) have been involved in conducting surveys, collecting genetic samples (e.g., Granroth-Wilding et al., 2017; Skrbišek et al., 2019), deploying wildlife traps, camera traps and acoustic recorders (Kays et al., 2017; Newson, Bas, Murray, & Gillings, 2017) and even analyzing the collected data (Swanson, Kosmala, Lintott, & Packer, 2016). The format of these efforts ranges from avid naturalists participating in structured data collection programs to observations made opportunistically by novices. Advances in statistics and computing have made it possible to extract increasingly meaningful information from both structured and unstructured community science programs (Sullivan et al., 2014).

Many studies have found that the quality of collected data is comparable to more conventional research (Callaghan, Lyons, Martin, Major, & Kingsford, 2017; Walker & Taylor, 2017) and at times performs even better (Callaghan & Gawlik, 2015; Swanson et al., 2016). Community science makes it possible to monitor at the spatial and temporal scales necessary to understand broad and complex conservation issues (La Sorte et al., 2017), can speed up data analysis (Swanson et al., 2016), and while community science is not free, it is more cost efficient at larger scales than conventional methods (Heigl, Horvath, Laaha, & Zaller, 2017; Lehtiniemi, Outinen, & Punttila-Dodd, 2020). Community science also has the potential to provide more consistent and long-term data than conventional monitoring. For example, even though some community science initiatives were impacted by the COVID-19 pandemic (Rose, Suri, Brooks, & Ryan, 2020), many others have continued to be an invaluable source of data when other field research programs were suspended.

It is worth noting that although community science and Indigenous knowledge and science seem to share many of the same qualities, they are very distinct knowledge systems with different worldviews (Leach & Fairhead, 2002; Miller & Davidson-Hunt, 2013). Indigenous knowledge is the understanding and philosophies developed by societies with a long history of interaction with the natural environment of their homelands and cultural values placed in sustainable resource use (UNESCO, 2017). Though both knowledge systems face conflict with acceptance in Western or “expert” science (Leach & Fairhead, 2002), community science has a more mechanistic approach, shared by Western science, while Indigenous science typically has a more non-interference experiential approach (Miller & Davidson-Hunt, 2013). These differences can provide unique opportunities for collaboration and knowledge co-production (Etiendem et al., 2020), especially for understanding resilience (Miller & Davidson-Hunt, 2013). We acknowledge that Indigenous science has its own strengths and examples of collaboration and co-management (Brook et al., 2009; Etiendem et al., 2020); however, in this paper we focus on highlighting the strengths of community science with the hopes of dissolving barriers to mutual participation and knowledge sharing.

Previous studies have shown that many factors, both ecological and social, contribute to resilient protected area design and management (Belote et al., 2017); however, studies are not always consistent in what they cite as factors contributing to resilience. Furthermore, given its proven reliability for other aspects of conservation research, community science could likely be used to augment data collection and research to help understand how any of these factors improve the resilience of protected area networks. Yet to the best of our knowledge, the contributions of community science to this area of research have yet to be explored. Here we use topic modeling to determine the main areas of focus in resilient protected area design, investigate how community science has already been applied to these areas, and identify gaps where it could be readily used. Our specific objectives were to: (a) determine the main topics of research in the literature focused explicitly on improving or maintaining the resilience of protected areas; and (b) determine the contributions of community science to each of these areas of research. We make no claims about what factors best contribute to resilience, but instead examined where research attention is focused and what role, if any, community science plays in advancing the current research in this area.
2 | METHODS

To determine the main topics of research in the peer-reviewed literature on resilient protected area design, we performed a literature search using Web of Science Core Collection on January 27th, 2020 with the following search string:

\[
TS = (\text{"protected area" OR reserve OR park OR preserve}) \text{ AND (ecolog* OR conserv* OR steward*)} \text{ AND (plan* OR design* OR optimiz* OR priorit*) AND (resilien*) NOT (engineer* OR energy)})
\]

Search terms were kept general to catch as much of the literature as possible, and to avoid biasing the results of our model. Additionally, we did not include community science or citizen science as search terms because they yielded zero and four results, respectively. This does not necessarily indicate a lack of community science in the protected area literature however, as there are a wide variety of terms that are used synonymously with community science (Eitzel et al., 2017), and often community science data is used but not clearly indicated (Tulloch et al., 2013). Of the 1,419 papers that our search yielded, 186 were retained after manually screening out papers that were not relevant to our subject.

We used Latent Dirichlet Allocation (LDA) to determine as objectively as possible the topics of research focus contained within this corpus. LDA topic modeling is a text mining technique used to detect patterns in a corpus and perform multimedia analysis (Jelodar et al., 2019). Applications include determining attention and sentiment across social media platforms, assessing political opinion or orientation, and elucidating meaningful topic structures within bodies of scientific literature (Griffiths & Steyvers, 2004; Jelodar et al., 2019), as done here.

LDA is a generative, probabilistic approach to understanding the latent topics in a collection of documents based on word frequency. It assumes that all documents are comprised of a mixture of topics, and that topics are represented by a collection of words that have a high probability of occurring together (Blei, Ng, & Jordan, 2003). Each word is first randomly assigned to a topic, at which point the “topics” are simply a random collection of words without any distinct theme. The algorithm then reassigns each word to a new topic based on both the probability of topics within a document (based on the assignments of other words in that document) and the probability of that word belonging to a topic across all documents. Words that occur together more frequently will therefore be reassigned to a common topic based on the probability of them occurring together within and across documents. For example, if the words “species,” “biodiversity,” and “abundance” are used together frequently, they are more likely to be grouped together as a distinct topic, which can then be classified based on the general idea that this collection of words conveys. Although the appropriate number of topics the model produces must be specified beforehand, the algorithm itself determines the word groupings and therefore the subject matter of each topic, as reflected by the body of literature. In this case, each abstract is treated as a separate document, and words are grouped into topics based on their conditional probabilities within and across abstracts. For a more detailed explanation on topic modeling using LDA, see Blei et al. (2003).

Using the “tidytext” package in R (Silge & Robinson, 2016), we tokenized the abstracts, splitting up each individual word in an abstract for each publication. We then removed stop words (common words that add no information about the specific topics) from the three lexicons available in the “tidytext” package—onix, SMART, and snowball. We also created a custom stop-word lexicon to remove words specific to our literature, but that add no additional value in generating distinct topics (see Supporting Information). Variations of the same term (e.g., plural) were not removed as this could influence the results of the model; however, this may cause some redundancy in the resulting terms associated with each topic.

One drawback with using LDA for topic modeling is that, while we can use it to determine the topics present in a corpus, the number of topics $K$ present in the corpus is not determined by the model itself. There is no single preferred method for choosing the optimal number, and different approaches may give different results. We therefore narrowed it down to an appropriate range using four different methods in the R package “ldatuning” (Nikita, 2020). The topic density approach uses the average cosine distance to measure the correlation between topics, with smaller values indicating more distinct topics (Juan, Tian, Jintao, Yongdong, & Sheng, 2009). According to the Kullback–Leibler divergence method,
the most orthogonal choice for the number of topics will minimize the difference between the topic-word and document-topic matrix distributions produced by the LDA model (Arun, Suresh, Madhavan, & Murthy, 2010). Maximizing the log-likelihood is a method of Bayesian model selection that calculates the likelihood of the data for a given number of topics (Griffiths & Steyvers, 2004). The final method involves a heuristic approach maximizing the Jensen-Shannon divergence between all pairs of topics (Deveaud et al., 2014). These metrics were calculated simultaneously for 14 iterations of the LDA, with \( K \) values ranging from 2 to 15 topics. Since we are only interested in the relative minima and maxima, all metrics were scaled between zero and one for ease of visualization. Once we narrowed down a range of the appropriate number of topics based on these metrics, we performed a qualitative assessment of topic coherence. This involved running multiple iterations of the model with an increasing number of topics \( K \), and deciding subjectively at which value \( K \) the resulting word combinations for each topic start to overlap and become less distinct. Using the R package “topicmodels” (Hornik & Grün, 2011), we then ran an LDA model using the Gibbs sampling method with 4,000 burn-in, 8,000 iterations and thinning to every 1,000th iteration.

The topics generated by the model were classified based on the top 20 most frequent words associated with each. These words are generated by the algorithm, then used to interpret what the theme of that topic represents. Documents represent a mixture of topics; some studies may cover multiple topics relatively evenly, while others may be heavily focused on one topic. We vetted a random sample of 10% of the corpus to assess whether the topics with the highest posterior probabilities for each study accurately reflected the subject matter based on the abstract. All analyses were performed using R version 4.0.1 (R Core Team, 2020).

Once the topics were established, we reviewed the corpus to assess whether and how they used community science. The presence of community science in the literature can be difficult to assess due to variation in the nomenclature used (Eitzel et al., 2017) and because the role of volunteers is sometimes poorly acknowledged (Tulloch et al., 2013). We therefore read all documents searching for any mention of community science or any synonymous terms or phrases that may have indicated the use of community science, such as citizen science, participatory approach, volunteer, local, atlas, and public. We also read each methods section to determine the source of monitoring data, and to look for any reference to the use of community science datasets. For the purposes of our study, community science was defined as any research where members of the public were actively involved in either the collection or analysis of data or samples. Regardless of whether the term community science or any of our synonymous terms or phrases were present in any particular study, we considered it to be a community science study if it matched this definition.

3 | RESULTS

The optimal number of topics in our corpus was between five and eight (Figure 1). Within this range, there was a drop in the metrics we wish to minimize (topic density and Kullback–Leibler divergence) and relatively high values for those we wished to maximize (log-likelihood and Jensen-Shannon divergence). Based on our
qualitative assessment of topic coherence, we chose to focus on five topics, since models with more than five topics specified resulted in topics that were less distinct, with similar words and themes associated with more than one topic.

The model generated the top 20 words associated with the five topics in our corpus, which we used to classify them. We chose to label the first topic “biodiversity,” as the words generated for this topic refer to species and population diversity, as well as species’ responses to threats and disturbances (Figure 2). Topic two we classified as “climate,” since the words associated with this topic refer to potential global climate impacts and capacity for adaptation. The collection of words associated with topic three suggest a focus on connected networks of protected areas and habitat patches, leading us to label this topic as “connectivity.” We labeled topic four “resources and ecosystem services,” since the words convey a focus on human needs and economic value. The words associated with topic five reflect multi-level governance and management schemes with an emphasis on frameworks for community involvement, leading us to label this topic “social governance.” Seventy-five studies explicitly mentioned a marine focus, 77 had a terrestrial focus and only six had a freshwater focus.

The order in which topics are presented does not reflect relative importance or frequency of that topic within the corpus. Each document is comprised of a mixture of topics in different proportions, and a chi-square
goodness-of-fit test on the summed posterior probabilities for each topic suggested that there was no significant difference in coverage among the topics ($\chi^2 [4, N = 5] = 0.56, p = .97$); that is, there was no significant difference in the prevalence of the five topics generated by our model in the corpus. However, after reviewing the content of 10% of the abstracts and comparing this to the topic allocation of each study based on our model, we determined that the categorization of papers into topics was only appropriate 73.7% of the time. Although this suggests there was some uncertainty in classification of individual papers, the method was nonetheless useful in objectively identifying the categories themselves.

None of the 186 publications from the literature search mentioned using community science in the title, abstract, keywords or methods as a means of collecting data or performing research to aid in the design or management of resilient protected areas. Two papers used atlas data collected by community scientists but without mentioning that this is how the data was collected; these papers were focused on climate and connectivity (Virkkala, Heikkinen, Kuusela, Leikola, & Pöyry, 2019) and biodiversity and resource management (Huggett, 2005). An additional study by Jones, Levine, and Jiddawi (2019) was designed to be easily compared to several previous studies, one of which used community science data; however, data quality issues were cited when the community science data contradicted the results of the studies using professionally collected data (Jones et al., 2019). The term “community science” was never mentioned in any document within our corpus. However, the terms “citizen science” or “citizen scientist” were mentioned in five papers, though they did not actually use it for empirical research but rather recommended it for future use. Several papers mentioned using participatory approaches, interviews, or local ecological knowledge, or reference the importance of social–ecological systems, but these were not considered community science for our purposes since they did not involve public participation in data collection or analysis.

4 DISCUSSION

Our analysis revealed that community science did not play a notable role in the five main topics of research on the resilience of protected areas identified in the literature. Only two studies used data collected by community scientists, but even in these cases it was not explicitly stated that community science was used. This is surprising given the wealth of examples in the literature of how community science is used effectively in other areas of conservation. Below, we further discuss and provide examples of how community science could help to advance each of the identified topics in the resilient protected area research in a way that is more efficient and effective than current approaches.

4.1 Biodiversity

Unsurprisingly, one of the key topics in the resilient protected area literature was the preservation of biodiversity. Biodiversity surveys and monitoring on the scales that are necessary to plan resilient networks and understand threats is challenging, and even basic monitoring is lacking in many protected areas (Leverington, Costa, Pavese, Lisle, & Hockings, 2010). Community science may greatly increase our knowledge of biodiversity beyond what can be accomplished with conventional monitoring strategies and better ensure resilience in protected areas against ongoing and pervasive threats. Due to its increased capacity for broad-scale and long-term biodiversity monitoring, community science may improve knowledge of communities, ecosystem and landscape dynamics. One of the most extensive uses of community science is for long-term, multi-species surveillance monitoring (Dickinson, Zuckerberg, & Bonter, 2010), which has proven useful for monitoring trends (Sauer et al., 2017), determining when species may be at risk (Maes et al., 2015), and catching gradual declines in common or foundational species that may otherwise have gone undetected (Rosenberg et al., 2019). These monitoring programs are some of the most widespread, consistent and long-term sources of biodiversity data and are often more cost effective than professional monitoring programs (Heigl et al., 2017).

Community science is also increasingly being used for hypothesis-driven research to assess threats to biodiversity. For example, community science was used to determine if habitat loss was a limiting factor in chimney swift decline (Fitzgerald, van Stam, Nocera, & Badzinski, 2014) and to demonstrate the seasonal components of population decline in Carolina wren populations (Link & Sauer, 2007). Additionally, the threats themselves are often the focus of community science efforts: it is used extensively to monitor invasive species (e.g., Crall et al., 2015; Goldstein, Lawton, Sheehy, & Butler, 2014), disease spread (Satterfield, Maerz, & Altizer, 2015), and road-kill occurrences (Heigl et al., 2017).

4.2 Climate change

Understanding how species are currently responding to large-scale climatic shifts is important for predicting how
species distributions and phenology will change and for determining the resilience of protected areas in the future (Hurlbert & Liang, 2012). However, agencies managing protected areas often lack funding for large-scale or long-term data collection essential for understanding how species adapt. Measuring adaptation requires field studies that combine baseline distribution data and monitoring species responses to change, such as flowering, breeding and migration times (Hurlbert & Liang, 2012; Monzón, Moyer-Horner, & Palamar, 2011).

Community science, which can be done for a fraction of the cost of conventional studies, may be the answer to collecting this valuable data for planning (Monzón et al., 2011; Worthington et al., 2012). Given that some community science programs are the most large-scale, consistent and long-term datasets available (e.g., Breeding Bird Survey; Sauer et al., 2017) and others are growing quickly (e.g., eBird; Sullivan et al., 2009), they can provide much needed baseline data (Donnelly, Crowe, Regan, Begley, & Caffarra, 2014; Tulloch et al., 2013). In addition, smaller community science programs can provide more localized data for predictive models that are needed for on-the-ground management in protected areas (Monzón et al., 2011).

Phenological monitoring, recording the timing of life-events in plants and animals that is influenced by temperature, lends itself well to understanding species reactions to changes in climate (Donnelly et al., 2014). Feldman, Žemaité, and Miller-Rushing (2018) found that if community scientists can measure phenology, even just once a year, the resulting data can potentially be more accurate than repeat structured monitoring. In fact, many community science-based phenology networks have already been set up with the goal of tracking climate shifts and long-term community science data sets have already been used to link change in phenological events in both birds and plants with climate change (Donnelly et al., 2014; Gonsamo, Chen, & Wu, 2013). Community science programs have also been established to conduct surveillance monitoring, to analyze imagery data (Kosmala et al., 2016), and even validate climate models (Saunders et al., 2020). In addition, community science has been used to track evolutionary change of species with shorter generations (Silvertown et al., 2011; Worthington et al., 2012).

### 4.3 Connectivity

Connectivity is recognized as a necessary element to support the resilience of protected area networks by the Convention on Biological Diversity (Convention on Biological Diversity, 2010). Populations that are better connected within a wider network are thought to have greater genetic diversity, recover better from disturbance (Underwood, Smith, Oppen, & Gilmour, 2009), adjust better to developing threats (Belote et al., 2017), and be more resilient to change (Minor & Urban, 2008; Underwood et al., 2009). However, connectivity is a complex subject that requires data on individuals and populations ranging from genetic diversity to landscape-level interactions—information that is lacking for many species and places (Friesen, Martone, Rubidge, Baggio, & Ban, 2019). Establishing species’ connectivity needs can therefore be aided greatly by the wealth of information available through community science datasets. Species distribution modeling, for example, is a data-hungry method used to establish species ranges and movement, and often employs community science data to meet data requirements (e.g., Bradsworth, White, Isaac, & Cooke, 2017; Schuster et al., 2019, and many others).

Genetic samples are commonly used to assess the degree of connectivity within protected area networks and populations (e.g., Coleman et al., 2011; Marra, Norris, Haig, Webster, & Royle, 2006), and growing evidence suggests that community scientists can reliably collect DNA samples (Granroth-Wilding et al., 2017; Skrbinšek et al., 2019), though these applications are still extremely underutilized. Since connectivity often spans entire landscapes, community science could be used to increase the number of samples collected as well as the area surveyed.

Furthermore, community science can offer solutions for understanding species habitat and connectivity needs on the private lands between protected areas and improving connectivity within these networks. With guidance and reliability checks from researchers, landowners could perform surveys (Aslan & Rejmánek, 2010), collect genetic samples (Granroth-Wilding et al., 2017), and set up camera traps (e.g., Kays et al., 2017) and acoustic recorders (Newson et al., 2017). The temporal and spatial resolution at which data can be collected also enables more dynamic conservation actions. For example, community science data was used to predict the timing and location of shorebird stopover sites on privately-owned lands during migration, leading to cooperation with landowners to provide suitable habitat by temporarily flooding their fields (Reynolds et al., 2017).

### 4.4 Ecosystem services and resource management

Protected areas are important not only for the preservation of biodiversity, but also the ongoing provision of resources and ecosystem services. Community science has previously been used to monitor indicators of
ecosystem function and service capacity (Vihervaara et al., 2015), to assess the value of ecosystem services (Newton, Hodder, Fernandez, & Kenward, 2013; Whitfield & Reed, 2012), to monitor the state of resources (Van Rijsoort & Jinfeng, 2005) and to assess the loss of ecosystem function and service provision (Meyfroidt, 2013). It has also been used to evaluate the complex relationship between ecosystem services and resources and biodiversity needs. For example, Wilsey, Jensen, and Miller (2016) used community science data to demonstrate that the grassland habitats that are vital to certain bird species also provide an estimated $900 million each year in ecosystem services, such as flood control. It can therefore contribute to protected area resilience by providing a better understanding of the state of our natural resources and their links with biodiversity, presumably leading to better management decisions and outcomes.

Frameworks exist in which community science monitoring can be used to evaluate the effects of management actions, allowing for adaptive learning and adjustment of said practices (Jordan et al., 2016). Such approaches are labor intensive and therefore could benefit greatly from the increased capacity of community science data collection. Involvement of local communities in management decisions can also complement other forestry management practices (Lefland, Huff, & Donahue, 2018). Community members that are included in these processes also achieve a better understanding of the services that biodiversity and ecosystems provide and are more inclined to consider sustainability and biodiversity in future planning and management initiatives (Becker, Agreda, Astudillo, Costantino, & Torres, 2005).

### 4.5 Social governance

Traditionally, protected area planning and management relied on professionals rather than local people (Knapp et al., 2014; Newton, 2011). However, for protected areas to be resilient, planning and management needs to be adaptive in nature and involve local communities (Camargo et al., 2009; Newton, 2011; Novellie, Biggs, & Roux, 2016). When programs involve community members, for example through community science, it can establish trust between conservation managers and the community (Aceves-Bueno et al., 2015), leading to more successful conservation management (Cooper, Dickinson, Phillips, & Bonney, 2007; McGreavy, Calhoun, Jansujwicz, & Levesque, 2016). Furthermore, strong community participation in protected area activities can link people with nature and reinforce their commitment to the environment (Aceves-Bueno et al., 2015; Jakobcic & Stokowski, 2019) and increase compliance (Camargo et al., 2009).

Community science is inherently participatory and aims to increase communities' understanding of the natural systems that surround them. An example of this is the Collaborative Forest Landscape Restoration Program (CFLRP), run in part by the US Forest Service, that aims to manage areas at risk of wildfires. To reduce conflicts over management strategies, stakeholders including local residents are involved from the beginning of the planning process. Together with the Forest Service, community science volunteers measure landscape variables and are involved in formulating research questions as part of their adaptive management scheme (McKinley et al., 2017). Allowing stakeholder participation at multiple stages reduces conflict with the local community and creates a firsthand understanding of the reasoning behind management decisions, leading to long term success of conservation programs that may be seen as controversial by some (Aceves-Bueno et al., 2015; Cooper et al., 2007). Lessons from this project can be applied in communities surrounding protected areas as many community members have a long-term understanding of the area and involvement will help protected areas be resilient into the future.

An example of how community involvement can lead to increased support for management is Mosquito Stopper, a project based in Maryland, USA that aims to address an invasive mosquito, the Asian Tiger Mosquito. Local residents are encouraged to collect data on mosquitos in their neighborhoods over the summer, which is then used by scientists to better understand the dynamics of the invasive species. Furthermore, the project was set up in hopes that residents would encourage government agencies to address the invasive species issue (Jordan, Sorensen, & Ladeau, 2017).

Inclusive approaches can also spread conservation and resource management outside the borders of strict protected areas. Protected areas can facilitate the flow of ecosystem services and biodiversity conservation into surrounding areas (Mattsson, Fischborn, Brunson, & Vacik, 2019). Fostering conservation actions in the surrounding areas will make for resilient protected areas (Akamani, 2012).

### 4.6 Study limitations

Our analysis is not comprehensive and undoubtedly leaves out other aspects of protected area design that can contribute to resilience. By limiting our scope to academic literature only, we possibly overlooked other important factors that may be critical to resilient protected area networks but are infrequently documented in peer-reviewed literature. For example, Indigenous science, community involvement or cultural considerations...
were explicitly mentioned in the title or abstract of 10 studies from our literature search, but Indigenous science was not prevalent enough in the literature to emerge as a main topic of resilient protected area research according to our model. We were somewhat surprised at this given the evidence that Indigenous-managed lands have equal or greater vertebrate species richness than protected areas (Schuster, Germain, Bennett, Reo, & Arcese, 2019) and contribute significantly to habitat connectivity (Hepburn et al., 2019). There are likely far more contributions than we are aware of that are documented in other ways besides academic publications, and relationships and collaborations with Indigenous knowledge holders may be far more prevalent behind the scenes.

Our literature search may have also missed studies that used alternative terms for resilience or that studied resilience without explicitly stating so. However, we chose to narrow our scope to literature that explicitly mentioned resilience as a goal or consideration of their study, rather than leave it to our own interpretation. We feel that our search terms gave us a representative sample of the literature to assess. Similarly, our search may also have failed to capture some studies that used community science for resilient protected area research. However, we believe our sample is sufficiently representative to illustrate the scarcity of community science in this research area. It is possible that some of the papers in our literature search did make use of community science data but simply did not mention it explicitly. For example, three papers referred to support from volunteers in the acknowledgement section but did not mention where their data came from in the methods. We recommend that all papers that make use of community science data make this clear, as this is an important part of the methodology, and not doing so makes it difficult to establish and acknowledge the contributions of community science in an area of research. Finally, it is possible that community science is being used to support on-the-ground management of protected areas for resilience but is not mentioned in the peer-reviewed literature. Nonetheless, given the potential utility of community science for designing and managing resilient protected areas, the lack of peer-reviewed literature in this area points to a key research gap. It is also suggestive of an implementation gap, but we would need to investigate community science projects outside of the literature to know for certain, which is beyond the scope of this study.

5 | CONCLUSIONS

Due to the breadth of its applicability in conservation biology, community science holds much promise for supporting research to design and manage resilient networks of protected areas. While we acknowledge that community science is not a perfect solution, our research indicates that its potential remains underutilized and undervalued. Community science approaches involve extensive, cost-effective data collection through a variety of methods and at broad spatial scales, with the potential to enable multi-species and ecosystem-level approaches to planning and prioritization. It is somewhat surprising that it does not appear to be applied to any aspect of research on protected area resilience.

Successful community science requires researchers to provide guidance and training, consider local knowledge and opinions, and be open to changing methods based on input from community members regarding feasibility. Moving forward, we suggest forming or using established community science programs as part of future research on resilient protected areas. Establishing groups to help in a specific area, such as the Friends of Gatineau Park (Friends of Gatineau Park, 2020), allows data to be collected on multiple species or broad-scale factors important to the resilience of that area on a more consistent basis, and could be used to study the resilience of this park (Friends of Gatineau Park, 2020). This would also allow community scientists to better identify challenges specific to their area and potentially result in more productive collaborations with researchers. Additionally, larger scale community science programs, such as eBird (Sullivan et al., 2009), could be used to aid research on resilience in protected areas across the globe. Community science is emerging as an important tool in land prioritization for protected areas at large scales, where data requirements are substantial (e.g., Lin et al., 2020; Schuster, Wilson, et al., 2019). There is a key opportunity to also use community science at smaller scales, to plan for and manage resilient protected area networks.

Determining what is required to design and manage resilient protected areas is difficult, requiring substantial information at broad temporal and spatial scales, which is often hard to come by. A potential solution to this problem lies with community science, which has applications relevant to each of the five topics around protected area design that we have identified as being the main areas of focus in the literature. We highlight the gap in the use of community science to address issues in resilient protected area research design and management and provide suggestions on how community science could be applied based on prior applications in conservation biology. Governments, and conservation managers faced with planning protected areas to meet new conservation goals (such as 30% land protection by 2030 [European Commission, 2020]), should strongly consider the role that community science can play in making these areas more effective and resilient to threats.
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CONFLICT OF INTEREST
The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS
Allison D. Binley, Caitlyn A. Proctor, Joseph R. Bennett, and Richard Pither contributed to the conception of the study. Allison D. Binley and Caitlyn A. Proctor drafted the manuscript. Allison D. Binley developed the methods and performed the analysis. Allison D. Binley, Caitlyn A. Proctor, and Sierra A. Davis contributed to the interpretation of the data. All authors contributed to the editing of the manuscript. Allison D. Binley and Caitlyn A. Proctor share first authorship.

DATA AVAILABILITY STATEMENT
The screened results of the literature search and script for analysis in R are available at: osf.io/nsauw.

ETHICS STATEMENT
This manuscript has not been published elsewhere.

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**SUPPORTING INFORMATION**

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

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