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Harnessing the Power of Community Science to Address Data Gaps in Arctic Observing: Invasive Species in Alaska as Case Examples

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ABSTRACT. The Arctic is undergoing large-scale changes that are likely to accelerate in future decades such as introductions and expansions of invasive species. The Arctic is in a unique position to prevent new introductions and spread of existing invasive species by adopting policies and actions aimed at early detection. Responding to threats from invasive species to minimize impacts to ecosystems, communities, food security, and northern economies will necessitate extensive observations and monitoring, but resource managers often face decisions without having adequate data and resources at hand. Local observing programs such as citizen science and community-based monitoring programs present attractive methods for increasing observing capacity that span contributory and co-created approaches while raising awareness of an issue among stakeholders. While the co-created model has been widely applied and encouraged in the Arctic context, contributory citizen science programs offer an additional tool for addressing observing needs in the Arctic. We showcase three contributory citizen science programs related to freshwater, terrestrial, and marine environments that have supported the objectives of the Alaska Invasive Species Partnership. We discuss criteria for achieving ARIAS priority actions at the participant scale related to participants' motivation and participants' understanding of the value of their contributions, at the programmatic scale, for example promoting accessible, reciprocal, and transparent knowledge exchange, and at the policy and science scale where management action is data driven. The approach is aimed at successful integration of citizen science into Arctic policy making. Finally, we discuss challenges related to broader global data collection and future directions for contributory citizen science within Arctic observing networks.

Key words: citizen science; community science; Arctic observing; alien species; monitoring; early detection; evidence-based policy

RÉSUMÉ. L'Arctique fait l'objet de changements de taille susceptibles de s'accélérer au cours des prochaines décennies, comme l'introduction et l'intensification d'espèces envahissantes. L'Arctique se trouve dans la position unique d'empêcher les nouvelles introductions et la propagation des espèces envahissantes actuelles grâce à l'adoption de politiques et de mesures visant à en faire la détection précoce. Réagir aux menaces des espèces envahissantes afin de minimiser leurs incidences sur les écosystèmes, les collectivités, la sécurité alimentaire et les économies nordiques nécessitera des activités d'observation et de surveillance d'envergure. Toutefois, les gestionnaires de ressources sont souvent tenus de prendre des décisions sans posséder de données et de ressources adéquates. Les programmes d'observation locaux, comme les programmes de science citoyenne et les programmes de surveillance communautaire, constituent des méthodes intéressantes d'augmentation de la capacité d'observation qui comportent des approches contributives et créées en collaboration tout en ayant pour effet de sensibiliser les parties prenantes aux enjeux. Bien que le modèle créé en collaboration ait été appliqué et encouragé à grande échelle dans le contexte de l'Arctique, les programmes de science citoyenne contributive offrent un outil supplémentaire pour s'attaquer aux besoins d'observation dans l'Arctique. Nous présentons trois programmes de science citoyenne contributive se rapportant à l'environnement d'eau douce, à l'environnement terrestre et à l'environnement marin, programmes qui s'inscrivent dans les objectifs du partenariat de l'Alaska en matière d'espèces envahissantes (Alaska Invasive Species Partnership). Nous discutons des critères nécessaires à l'atteinte des mesures prioritaires de l'ARIAS à l'échelle du participant, soit en matière de motivation des participants et de leur compréhension de la valeur de leurs contributions, à l'échelle programmatique, par exemple en

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faisant la promotion d'un échange de connaissances accessible, réciproque et transparent, et à l'échelle des politiques et des sciences pour lesquelles les mesures de gestion sont fondées sur les données. La démarche vise l'intégration réussie de la science citoyenne dans l'élaboration des politiques touchant l'Arctique. Enfin, nous discutons des défis inhérents à la collecte générale des données globales et à l'orientation future de la science citoyenne contributive au sein des réseaux d'observation de l'Arctique.

Mots clés : science citoyenne; science communautaire; observation de l'Arctique; espèces étrangères; surveillance; détection précoce; politique fondée sur des données probantes

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INTRODUCTION

Native biodiversity of the Arctic provides sustainable resources that support rural and urban cultures, global ecological processes, and economies of the North (Johnson et al., 2007; Courtney et al., 2018). Currently, Arctic freshwater, terrestrial, and marine ecosystems remain largely uninvaded by alien species because of the cold climate, remoteness, and sparse human population (Lassuy and Lewis, 2013; Wasowicz et al., 2020). However a rapidly changing climate, increased disturbances, and more pathways of introduction are making Arctic habitats more accessible and suitable for invasive species (Luizza et al., 2016; Droghini et al., 2020; Wasowicz et al., 2020). Invasive species are defined with regard to a particular ecosystem, as a "non-native organism whose introduction causes or is likely to cause economic or environmental harm or harm to human, animal, or plant health" (DOI, 2021:i).

Preventing the introduction and spread and managing the impacts of invasive species across large landscapes and aquatic systems are significant challenges for natural resource managers in the Arctic. To make well-informed decisions, managers need timely and accurate data that are often not available because of the high financial costs and challenging logistics of fieldwork in the North. Resource management agencies and researchers often cannot achieve adequate spatial coverage with their crews, and remote sensing data cannot detect the presence of an invasive species until an invasion site is past the incipient stages and is costly to respond to (Williams et al., 2018). Local residents' on-the-ground observations are increasingly being used by researchers and land managers for data-driven decision making to improve conservation outcomes not only in the Arctic but across the globe (Barnard et al., 2017; Williams et al., 2018).

To combat invasive species throughout the circumpolar North, the Arctic Council developed the Arctic Invasive Alien Species Strategy and Action Plan (ARIAS Plan) (CAFF and PAME, 2017). The ARIAS Plan identifies three priority actions: 1) inspire urgent and effective action, 2) improve the knowledge base for well-informed decision making, and 3) undertake prevention and early detection and rapid response initiatives. The U.S. Arctic Invasive Species Working Group and the Alaska-based invasive species coordination network—the Alaska Invasive Species Partnership (AKISP)—treat all of Alaska as part of the Arctic as defined by geopolitical boundaries (AKISP, 2020).

Members of the AKISP are dedicated to conserving and restoring the native resources of the Arctic. To achieve the vision of the ARIAS Plan and other federal, state, and tribal strategic plans, the AKISP is 1) implementing a coordinated interagency invasive species communications strategy (AKISP, 2020), 2) conducting habitat suitability assessments (Luizza et al., 2016), vector analyses (Schwoerer, 2020; Schwoerer et al., 2020b), and species risk prioritization rankings (Carlson et al., 2008; Droghini et al., 2020), 3) implementing best management protocols, developing detection standards, conducting inspections at critical control points, and bolstering early detection surveys of priority species, and 4) supporting and promoting citizen-based efforts to assist the detection and management of invasive species through community science. The fourth strategic action is the subject of this paper.

AKISP, and particularly federal and state agencies, are striving to increase engagement and investment of entities with large geographic reach, such as tribes and Indigenous communities in Alaska and industries (tourism, resource development, etc.) (DOI, 2021). Even though tribal strategic plans are primarily natural resource focused, these plans often align with citizen-based observation methods and practices (AKISP, 2018; DOI, 2021). The AKISP acknowledges and values input, leadership, and participation from the federal, state, tribal, and industry representatives and private citizens who collectively make up the AKISP (AKISP, 2018; DOI, 2021).

Alaska and the Arctic region are in a unique position to prevent new introductions and the spread of existing invasive species by adopting policies and early detection actions that so far have been shown to be effective in Alaska. Increasing observer involvement from diverse communities across the Arctic has led to increased rates of early detections through the availability of local observers and resources capable of verifying and responding to new infestations (AKEPIC, 2020). Here, we discuss models and levels of public engagement that can enable successful long-term implementation of broader observer capacity across the Arctic and describe three case examples from freshwater, terrestrial, and marine ecosystems where citizen participation has been successful in meeting the goals of the ARIAS Plan.

Models of Public Participation

Local observing efforts such as citizen science and community-based monitoring (CBM) programs present an attractive approach for increasing observing capacity for invasive species in the Arctic. Both citizen science and CBM span a spectrum of partnerships and engagement levels between public community members and professional researchers or land managers with the goal of generating new scientific research or producing long-term monitoring datasets, respectively (Danielsen et al., 2010; Shirk et al., 2012; Johnson et al., 2015). Shirk et al. (2012) define the public participation spectrum ranging from contributory to co-created projects.

At the "contributory" level of participation, researchers design projects, and members of the public primarily contribute data and consent to its use for the stated goal of the project. Many contributory projects are hypothesis-driven or have long-term monitoring goals aligned with regional management priorities, span a large geographic area, and have limited interaction among the participants during the data collection phase. Participants may contribute to the program for a limited time or over multiple years and do not necessarily need a long-term connection to a focal geographic location. Two examples of long-running contributory citizen science projects in Alaska are the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) and the National Audubon Society's Christmas Bird Count, which has been in existence nationally since 1901 and in Alaska since 1941 (Dunn et al., 2005; Reges et al., 2016).

At the "co-created" level of engagement, public participants and researchers together design the project and are involved in most or all aspects of the research process (Danielsen et al., 2009; Gofman, 2010; Shirk et al., 2012). In the Arctic, the co-created model is currently receiving significant emphasis in the design of long-term monitoring programs aimed at observing environmental change (Kouril et al., 2015; Danielsen et al., 2018). Co-created projects often tie specific information or management needs arising within a community to broader-scale observing initiatives and policy objectives (Danielsen et al., 2009). Co-created projects also directly address and reduce the power dynamics and colonial history of science in Indigenous communities (David-Chavez and Gavin, 2018). For example, the Piniakkanik Sumiiffinni Nalunaarsuineq (PISUNA) program is led by the Greenland Ministry of Fisheries, Hunting, and Agriculture (Danielsen et al., 2014; PISUNA, 2020). It uses a co-created approach with the stated goal of "strengthen[ing] the involvement of fishermen, hunters and other environmentally interested people in the documentation and management of living resources" (PISUNA, 2020).

Many citizen science projects tend toward the "contributory" end, though co-created citizen science programs are not uncommon, particularly projects with environmental justice goals (Shirk et al., 2012). CBM is generally towards the "co-created" end of the participation spectrum, though some CBM projects, such as standardized multi-community water quality monitoring, operate as contributory programs (Danielsen et al., 2010; Shirk et al., 2012).

The trade-offs between contributory and co-created models of engagement are significant and well documented (Alessa et al., 2015). Within the Arctic context, co-created projects often have limited geographic scope and involve a small number of volunteers or paid local observers in each community. Co-created projects most often are long-term initiatives with a significant time investment to develop and implement, while contributory projects can be quickly launched with the aid, for example, of online data reporting tools (Shirk et al., 2012). Community members involved in co-created projects usually have significant local experience or traditional knowledge of the system or processes being monitored. In the Arctic, participants in co-created projects tend to be male subsistence hunters and fishermen (Danielsen et al., 2021).

In contrast, contributory projects can have a much larger geographic range, and participants may or may not have prior knowledge of the phenomena being observed, as training is often provided as a component of participation. Contributory programs tend to attract a wide range of volunteers, such as younger community members who might not be recognized as local experts within Indigenous villages (ELOKA, 2020). Therefore, while co-created approaches are essential for advancing equity, accessibility, and justice along with increased knowledge in Arctic science, contributory projects still have an important role within the Arctic observing toolbox and promote an even more inclusive approach to observing. Importantly, because of their shorter mobilization periods and broader reach in engaging a larger number of participants, contributory projects provide larger data sets with a broader geographic scope than would be achievable through co-created projects alone (Baker et al., 2012; Chandler et al., 2017). We do not downplay the importance of existing or future co-created programs, but instead promote the additional value of contributory programs running alongside co-created programs to observe Arctic change across expanded temporal or spatial scales.

Connecting Arctic observations to management and adaptation actions is an important reason to support sustained Arctic observing. Despite the development of observing platforms that aim to integrate Indigenous and local knowledge into environmental management decisions, such information remains largely underutilized by Arctic decision-making bodies (Danielsen et al., 2020). These elements were recognized in one of the key recommendations from the 2020 Arctic Observing Summit that stated the need to identify gaps in Arctic observations to inform adaptation and policy responses (Arctic Observing Summit, 2020). We highlight three case examples related to contributory projects the authors developed and implemented as members of AKISP dealing with invasive species in Alaska's diverse terrestrial, marine, and freshwater ecosystems, where citizen science has contributed to the broader Arctic observing system and local management and monitoring. We relate each of the examples to priority actions outlined in ARIAS and describe the relevance of local observing efforts that can be adapted more broadly throughout the circumpolar North (CAFF and PAME, 2017).

CASE EXAMPLES

For each case example, we first describe the management or monitoring problem followed by the data collection approach. We then illustrate how the results addressed research objectives and ARIAS priority actions. Finally, we discuss criteria that are important for achieving ARIAS priority actions and how contributory citizen science approaches could further meet longer-term Arctic observing needs (Table 1).

Quantifying the Impact of Aquatic Invasive Species

Two species of the submerged aquatic plant of the genus *Elodea* (*Elodea canadensis* and *Elodea nuttallii*), hereafter *Elodea*, are the first submerged aquatic invasive species (AIS) identified in Alaska. *Elodea* likely made it to Alaska through the aquarium trade. In 2010, it was discovered in urban parts of the state and in 2015 in Lake Hood, the world's busiest seaplane base. Seaplanes and other human and natural transmission have introduced *Elodea* to remote wilderness areas across Alaska (Schwoerer and Morton, 2018). Once introduced, *Elodea*'s explosive and dense plant growth changes freshwater systems in ways that can threaten Alaska salmonids by decreasing dissolved oxygen levels and altering habitat (Schwoerer et al., 2020a), affect vital salmon fisheries (Schwoerer et al., 2019a), and create safety hazards for seaplane pilots (Schwoerer et al., 2020b). Since Alaska is mostly roadless, small single-engine propeller planes with floats play a large role in commercial and private transportation during summer (Gray, 1980). There are approximately 80 seaplane charter and air taxi operators in Alaska and over 3000 seaplane-certified pilots live in the state (FAA, 2015). Alaska residents and tourists use seaplanes to access remote lakes for fishing, hunting, and other recreation. *Elodea*'s dense and explosive growth can prevent pilots from accessing these lakes, creating a strong incentive to help prevent further spread.

We contacted a random sample of 1000 pilots flying for personal reasons, all 80 of Alaska's commercial seaplane operators, and all 64 pilots flying seaplanes for the government. Volunteer pilots contributed data using an electronic mapping tool with which they could precisely identify flight destinations and annual flight frequencies. A total of 482 pilots and 52 businesses contributed data through the project web tool. The data are archived at the Arctic Data Center to ensure public access and data discovery through a global network of data repositories such as DataOne (Schwoerer et al., 2019b; Schwoerer, 2020).

The project had three key outcomes. First, we collected flight destinations for seaplanes to inform AIS pathway models. We predicted the probability of introducing *Elodea* into each of 727 waterbodies that pilots identified (Schwoerer, 2020). Second, we showed seaplane pilots the hidden economic cost of unintentionally carrying *Elodea* from urban source lakes to remote destinations. We estimated the non-market loss in recreation value associated with an *Elodea*-invaded lake to equal $185 per seaplane trip on average (Schwoerer et al., 2020b). These hidden economic costs raised awareness and nudged pilots to minimize transmission risk. Third, we informed management decisions by developing social-ecological models that weighed benefits and costs for a set of management alternatives. We combined structured expert knowledge and market valuation to forecast damages to commercial fisheries affected by *Elodea*, weighing costs and benefits of taking action (Schwoerer et al., 2019a).

Our work was inspired by the demand for more sophisticated tools to inform active AIS risk management in the Arctic and is a steppingstone towards a more proactive risk management approach for *Elodea* and other aquatic invasive species yet to arrive in the circumpolar Arctic. The collected flight path data bolstered urgent and rapid multiagency coordination for *Elodea* prevention measures across community, tribal, state, and federal partners. In addition, the data informed a pathway model showing the risk of introducing AIS via seaplanes and assisting resource management agencies in prioritizing early detection and eradication efforts. This project has been essential in raising awareness about invasive species risks with many key audiences including aviation groups and state and federal legislators. As a result, participation by stakeholders such as these has increased in statewide planning efforts and participation in early detection efforts. (AKISP, 2020). In our work on invasive species pathways, we found seaplane pilots to be particularly proactive and, in some cases, leading outreach efforts to increase understanding of the consequences of AIS transmission among seaplane pilots. For example, the U.S. Seaplane Pilots Association has been working with the Western Regional Panel's Seaplane Inspection and Decontamination Workgroup to develop new standard operating protocols that reduce the risk of seaplanes transmitting aquatic invasive species such as zebra and quagga mussels (Western Regional Panel, 2018). The Western Regional Panel on Aquatic Nuisance Species is a panel of public and private entities formed in 1997 to help limit the ecological and economic impacts of AIS introduction and spread into the western region of North America (Western Regional Panel, 1997).

Together with one of Alaska's largest seaplane operators, we are currently developing and testing a broader citizen science data collection approach that would engage volunteers we identified through the survey with seaplane pilots. Of the 534 pilots responding to the survey, about

TABLE 1. Summary showing how contributory citizen science case examples apply to ARIAS priority actions.

	Aquatic	Terrestrial	Marine
ARIAS priority areas:			
Inspire urgent and effective management action	Flight path data bolstered urgent and rapid multiagency coordination for *Elodea* prevention measures across community, tribal, state, and federal partners	Phenological data collected informed timing of invasive plant control measures; rural participants eradicated an early *Melilotus* introduction	Community members urged legislators to provide agencies with funding for cleanup
Improve the knowledge base for well-informed decision making	Spread risk models produced allowed land management agencies to prioritize monitoring of high-risk waterbodies	Data were used for peer-reviewed scientific publications and participant knowledge and awareness of invasive species issues	Increased community awareness of marine invasive species resulted in an uptick in monitoring effort and associated reporting
Undertake prevention and early detection and rapid response initiatives	Data on seaplane flight paths and vector potential heightened awareness of the issue among pilots and their social networks leading to increased awareness and behavior change to keep rudders clean during take-off	Participants increased efforts to prevent and remove invasive plants	Early detection of a global marine invader (*D. vexillum*) initiated direct management action to reduce spread risk and fostered local engagement in subsequent research projects
Indicators:			
Source of motivation	Awareness that pilots are contributing to the problem but are also affected by unintentionally transmitting aquatic invasive species	Concerns about food security, peer groups, local connection to land and waters	Concerns about biodiversity, economic impacts, and food security. Local connection to land and waters
Incentives	Small token of appreciation, $2 bill enclosed in letter of invitation	Immediate feedback from scientists on the collected data, data included in scientific publications, program awards and recognition, supplementary professional development credits	Hands-on learning about local ocean ecosystems with a group of experts
Target audience	Targeted high-income households, personalized invitations emphasized the short time investment for participating	Youth, families, educators, environmental managers, and concerned citizens	Individual community members, families, and members of the Sitka Tribe of Alaska
Geographic scale of engagement	482 volunteer pilots and 52 businesses across Alaska	247 volunteers at 106 monitoring sites in 17 communities across Alaska	23 volunteers from the community of Sitka, Alaska
Participants' time investment	25 minutes total on average per participant	Approximately 30 min per week throughout the summer	Up to three days with a few people participating longer

a quarter wanted to volunteer for future monitoring and research efforts. Volunteers would install cameras onto their seaplanes to take video imagery of the pontoon's rudder assembly where AIS transmission occurs. The project's objectives are to improve understanding of AIS transmission processes, identify the spatial risk domain, and improve models to inform early detection and rapid response.

Our case example shows how rigorous data collection with help from the public—here seaplane pilots—can improve our understanding of long-distance AIS dispersal and inform resource management response across large spatial scales. It encourages other Arctic countries to design similar contributory community science approaches to collect data informing proactive management of aquatic invaders (e.g., Brazilian waterweed [*Egeria densa*], European green crab [*Carcinus maenas*], zebra mussel [*Dreissena polymorpha*]) that are spreading north into a warming Arctic (Karatayev et al., 2015; Reimer et al., 2017; Kent et al., 2018).

Variation in Invasive Plant Phenology

In boreal and Arctic communities, the harvesting of wild plants, particularly wild berries, contributes significantly to a subsistence diet (Thornton, 1998; Hupp et al., 2015; Boulanger-Lapointe et al., 2019). In the Arctic, where terrestrial non-native plant spread remains small relative to other regions (Wasowicz et al., 2020), communities are increasingly implementing prevention and control measures to protect important wild berry harvesting areas (Spellman and Swenson, 2012; Leask and Winter, 2017). Concern about the increasing variability of wild berry yields in Alaska (Hupp et al., 2015) and the potential for invasive plants to further influence the growth and pollination of subsistence berries (Spellman et al., 2015) motivated the Melibee Project, a citizen science project based at the University of Alaska Fairbanks. Across the three years of the Melibee Project (2012 – 14), 247 adults and youth from 17 urban and rural Alaska communities made weekly observations of when plants flower to investigate the potential for invasive white sweetclover (*Melilotus albus*) to alter pollination of native blueberries (*Vaccinium uliginosum*) and cranberries (*V. vitis-idaea*). Data were made publicly available through the Hands on the Land website in the form of graphs illustrating changes in the seasonal and geospatial variation in time of flowering (phenology) (Spellman et al., 2014). We compared the data collected by participants with phenology data obtained from herbarium specimens from across North America to assess the strengths and weaknesses of models based on herbarium and geographic data (Spellman and Mulder, 2016). These two datasets complemented data from a field experiment that examined changes in pollination, fruit set, and seeds per fruit when the flowering times of white sweetclover and berry species completely overlapped (Spellman et al., 2015; Spellman and Mulder, 2016). These data can be used to assess the potential overlap in flowering times of the invasive plant and berry species across the diverse ecoregions of Alaska.

Our publicly available dataset covered a relatively large geographic area and piqued the interest of land managers who were interested in spatially specific flowering times to inform their eradication efforts for white sweetclover (Alaska Soil and Water Conservation Districts, pers. comm., 2013). The dataset also motivated large-scale surveys of invasive plants near subsistence use areas (Robinette, 2015) and further analysis of the risk of an invasive plant to local berry patches (Spellman and Swenson, 2012). Key elements for successful and high-quality data collection included 1) extensive training on data collection, 2) open and accessible data to all participants in an easily usable form, and 3) promoting the use of the data and collaboration across participants, scientists, and land managers through the Alaska Invasive Species Partnership (Spellman, 2013). In addition, we documented behavior changes of participants involved in the Melibee project through a retrospective pre-post evaluation survey (Spellman, 2015). Most notably, nearly half of the respondents increased their frequency of deciding not to plant an ornamental because they thought the species might be invasive, and 44% increased the frequency with which they pulled invasive plants in their yard or neighborhood. Participants living in a remote village in southwestern Interior Alaska provided early detection of white sweetclover growing in an area where heavy equipment had been brought in from the road system to install a communication tower. They were able to submit an observation and eradicate the species from their village before it went to seed (AKEPIC, 2020).

Since the Melibee Project concluded, we have initiated three other citizen science projects, with an increasing emphasis on expanding the population of participants and making the projects more relevant and more accessible to all community members, especially youth. We used four strategies to expand participation and reduce trade-offs between contributory and co-created program models (Spellman et al., 2019). First, we linked the questions asked and the data collected explicitly to the concerns that community members have expressed. For example, in our most recent effort, the Winterberry Project, we moved from focusing on flowering times of fruit-producing species to the fate of the fruits themselves, as climate change may be affecting the timing of fruit loss in fall and winter (Mulder and Spellman, 2019). This timing is a concern to many communities, as harvesting berries competes for time with other fall activities such as hunting. Second, we visited most communities to ensure that community members personally interacted with the scientists and that the scientists understood the communities collecting the data. We also made sure researchers spoke with every volunteer, even those we did not meet in person. Third, we deliberately incorporated culturally responsive strategies, such as prioritizing personal and local experiences and embedding the citizen science experience within a learning framework based on storytelling. This approach changed the nature of the relationships within a contributory program and shifted the demographics of the participants. Approximately half of the 247 participants in the Melibee Project were youth and a quarter were Alaska Native or members of other groups underrepresented in STEM (science, technology, engineering, and mathematics) fields. In the Winterberry Project, 89% of the 1545 participants to date are youth and 43% are Alaska Native or of other underrepresented groups (Spellman et al., 2019). Fourth, we greatly expanded the availability of data to youth by making the data immediately available, easily interpretable, and by holding youth science symposia, family and community nights, and "data jams" with each group of volunteers. All participants have access to the full dataset, resulting in youth and adult presentations at events such as science fairs, conferences, and other forums. Results have also been presented by the researchers at professional meetings and, upon publication in peer-reviewed journals, will become publicly available. These multiple avenues of distribution through participants and scientists should encourage greater use by land managers.

Many volunteers have collected data over several years and in some cases have participated in two or even three projects. We believe this is in part because our projects are increasingly a two-way street: they provide high-quality data to scientists over enormous spatial scales and years that could not otherwise be obtained, but, crucially, they also provide information of direct interest and use to the participants. Participants' ideas and insights are incorporated into the data collection and interpretation. For example, while the data collected under our protocols may tell us when fruits are removed from plants, local residents often provide insights into which animals are removing them. While projects that are collaborative can be challenging and time consuming, they provide invaluable information and strengthen human connections across large regions that are essential for obtaining large spatial coverage of observing capacity.

Detecting and Responding to a Marine Invasive Species

Arctic marine systems are relatively poorly studied, and information about status, habitat requirements, and relative distribution and abundance of marine fish and invertebrates is incomplete and unavailable for large expanses of the Arctic nearshore and shelf waters (Huntington, 2000; Holland-Bartels and Pierce, 2011). Integrating this place-based knowledge can serve important roles in managing ecosystems before and after invasion (Reo et al., 2017).

Few non-native marine species have been observed in Alaska coastal ecosystems. The predicted northward range extension of invasive marine invertebrates, especially under warming ocean temperatures (Ruiz and Hewitt, 2009; de Rivera et al., 2011; Reimer et al., 2017; Ruiz et al., 2017; Jurgens et al., 2018), prompted the establishment of a community-based monitoring network to facilitate early detection of new species. For reporting the status of invasions and informing management actions, up-to-date knowledge from community-based monitors is needed (Lehtiniemi et al., 2020). Observance by Sitka Tribe of Alaska monitors of known invasive colonial tunicates associated with anthropogenic infrastructure in a Southeast Alaska harbor led to a marine invasive species-focused BioBlitz to investigate the extent and diversity of species established in area waters and to inform the local community about aquatic invasive species generally (AES, 2021; Jurgens et al., 2018). In this case, early detection of a global invader by a motivated and concerned community led to investment in management actions over the past 15 years.

A BioBlitz involves participants focused on the collection of biotic and abiotic data within a specific space and time (AES, 2021). These events are popular with community participants working alongside scientists, providing enjoyable learning experiences, engaging new audiences in biodiversity issues, and inspiring positive action (Postles and Bartlett, 2018). Scientists and policy-making bodies need and receive large amounts of current, accurate marine data gathered by volunteers each year (Baker et al., 2012). These opportunities are valuable beyond the initial event because local residents trained during the BioBlitz are often the first to notice subsequent changes in fish and wildlife populations (Holland-Bartels and Pierce, 2011).

In June 2010, community members of Sitka, Alaska, joined university students, professors, and experts, along with state, federal, and Sitka Tribe of Alaska biologists in a BioBlitz. Teams were in search of six conspicuous non-native species previously unknown in Alaska waters, as well as the two colonial tunicate invaders, *Botrylloides violaceus* (Oka, 1927) and *Botryllus schlosseri* (Pallas, 1766), known to occur in at least one local harbor (Ruiz et al., 2006; Wang, 2011). Among other human-mediated pathways, coastal invasive species are commonly associated with and transmitted by in-water artificial structures such as mariculture (marine-based aquaculture) infrastructure, docks, and transient vessels (Carman et al., 2010; Fletcher et al., 2013; Lehtiniemi et al., 2020). Intensive searches occurred at a local aquatic farm, public and private docks, the hulls of moored boats within city harbors, and prioritized shorelines. Upon completion of the BioBlitz, in addition to the two known tunicates, observations included one new putative target species. The new organism, also a colonial tunicate, appeared to be *Didemnum vexillum* (*D. vexillum*), also known as carpet sea squirt. Samples of the tunicate were analyzed using molecular methods to confirm its identity (Cohen et al., 2011). Since 2010, *D. vexillum* has not been detected during CBM efforts or BioBlitz events in other coastal communities in Alaska or by surveys of nearshore habitats in Sitka. At this time, the known distribution of *D. vexillum* is contained within Whiting Harbor, Sitka, where it was first detected.

Individuals who spend time in the marine environment will most likely also observe novel species while harvesting resources from the sea. Engagement with the nearshore environment is essential when harvesting food from the sea. Of surveyed households in rural Alaska, between 92% and 100% reported using wild fish resources and nearly all harvest fish for themselves and community members (Fall et al., 2019). Fish account for 53% of the usable wild food mass harvested by the average Alaska subsistence user, with shellfish contributing an additional 3% of mass (Fall et al., 2019). Sitka Sound is known for its rich and valuable fisheries and habitat. Whiting Harbor, within Sitka Sound, has important spawning grounds for Pacific herring (*Clupea pallasi*). Herring are a vital component of the coastal food chain and the local commercial fishing economy, and herring roe is a highly valued subsistence food for the Indigenous population. Also, groundfish (lingcod, rockfish, and sablefish) and shellfish (abalone, clams, geoduck, and scallops) are harvested commercially and by households.

Upon confirmation of the presence of *D. vexillum* in Alaska, Sitka residents, regional marine invasive species experts, and management agencies began investigating options for rapid response. When funding was initially unavailable to undertake response actions, community leaders lobbied decision makers to include funding in agency budgets. Locals volunteered to assist with cleanup efforts, research projects (McCann et al., 2013), and surveys. They reported observations of organisms thought to be *D. vexillum*. As funding became available, with engagement by community members and informed researchers, management agencies undertook removal of *D. vexillum*-infested aquatic farm infrastructure to eliminate source populations in the water column. Because the Whiting Harbor *D. vexillum* is the only known infestation in the Arctic, the patchy distribution established on submerged debris and the seabed posed a high level of concern for future spread to new areas in Sitka Sound. State and federal management agencies collaborated with the Smithsonian Environmental Research Center (SERC), Marine Invasion Lab to investigate the feasibility of controlling *D. vexillum* in Alaska (McCann et al., 2013).

Over the course of the next six years, SERC, the Alaska Department of Fish and Game, and the Bureau of Land Management conducted two experiments to test the feasibility and efficacy of applying biocides within contained treatment areas (based on McCann et al., 2013)

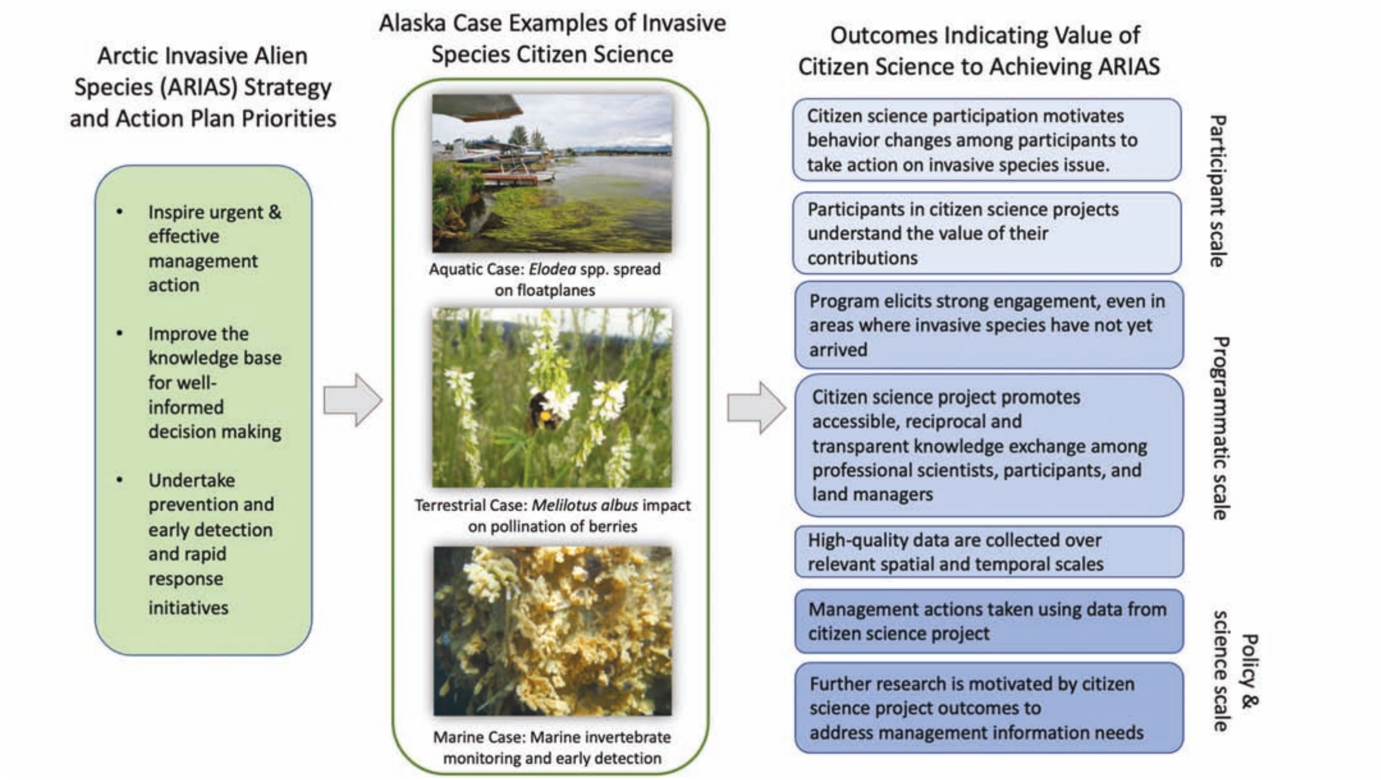

FIG. 1. Outcome indicators for contributory citizen science programs achieving ARIAS priority actions at participant, programmatic, and policy and science scales.

to cause mortality to *D. vexillum* in situ. Results from the first study identified chlorine as an effective biocide to remove the benthic invader when administered according to treatment protocols (Davidson et al., 2016). The methods implemented in Davidson et al. (2016) were refined for the second study; chlorine was applied to *D. vexillum* colonies within scaled-up treatment areas. Conclusions from the second study indicated greater tunicate mortality occurred when treated colonies were established on flat, mixed coarse substratum. Effectiveness was reduced when the substratum became more complex. Though few eradication attempts have been successful in marine environments (Williams and Grosholz, 2008; Hopkins et al., 2011; Lehtiniemi et al., 2015), these studies suggest eradication is feasible; however, significant resources and time commitments are necessary for success (Davidson et al., 2019). In the absence of further control efforts, targeted monitoring of the infestation is necessary, especially in vulnerable and sensitive areas. A long-term network of community-based early detection monitors continues to sample for non-indigenous fouling invertebrates in coastal communities within the Gulf of Alaska, and the Alaska Department of Fish and Game maintains an online reporting portal and hotline for contributed reports of unusual organisms. These approaches are accompanied by routine surveys for *D. vexillum*. Citizen engagement, paired with agency and policy-maker collaborations, provides hope for long-term conservation in localized areas (Stephenson et al., 2012).

DISCUSSION

Recent publications by Arctic Council working groups emphasize threats to native biodiversity (CAFF, 2017; Lento et al., 2019). These status assessments identify rapidly shifting climatic conditions as one of the leading causes of native biodiversity loss. The reports also highlight that existing data are not enough to describe biodiversity trends across all ecoregions of the Arctic and that increased monitoring efforts are required to improve the understanding of biodiversity change. Recent efforts to systematically assess the status of invasive species throughout the Arctic region have also highlighted the need for a more comprehensive approach to documenting locations of non-native species and vectors of spread (Wasowicz et al., 2020). The case examples we presented show how contributory citizen science projects can help to achieve the three main priority actions under ARIAS (CAFF and PAME, 2017). In Figure 1 we summarize programmatic outcomes that were important for achieving ARIAS priority actions and categorized outcomes as applicable to participants, program design, policy decisions, and scientific knowledge.

At the participant scale, we observed that, in all three case examples, participation in scientific research and environmental monitoring motivated participants to change their own behavior or to act locally and contribute solutions to the issue under investigation. This increase in public awareness and behavior is a common outcome found in other contributory citizen science projects (Evans et al., 2005; Jordan et al., 2011; Crall et al., 2012). To achieve increased awareness, however, participants need to understand the value of their contributions, particularly when collected data show absence instead of presence of the researched phenomena. Especially in the case of invasive species, frequent and consistent communications between scientists and participants should emphasize the value and applicability of citizen science data for policy and management decisions. If participants have a sense of ownership in data collection, the resulting management actions and policies have higher public acceptance than would otherwise be the case (Carlson and Cohen, 2018). In addition, strong relationships between researchers and participants are key for achieving the longevity needed for Arctic observing and successful management outcomes.

Besides providing frequent feedback, scientists can also build stronger and more reciprocal relationships if they acknowledge and reward participants for their effort. Rewards can range from small tokens of appreciation for participation, to volunteer awards (e.g., most data collected, most foul weather days braved, most friends brought out to monitor), to larger stipends for longer-lasting research activities. Additional incentives flow from an open and transparent exchange of knowledge, especially when it becomes clear that the contributed data are having an impact on management or the development of further research. Frequent feedback for participants can also include data-generated infographics that participants can share with their communities. This exchange can raise much broader awareness and leverage potential community efforts to take or contribute to action. Moreover, the sharing of citizen science data among participants, scientists, resource managers, and the public through open science frameworks provides a foundation for transparency and innovation towards actionable research (Munafò et al., 2017; Kenens et al., 2020).

At the policy and science scale, the case examples illustrate that contributory citizen science programs can provide valuable resources to quickly raise broad public awareness and inform early detection and rapid response efforts. Resource managers often face decisions requiring quick action to avoid damage to ecosystems and economies but lack quantitative information to support decisions. Managing invasive species is one situation where rapid response can minimize long-term costs, but where persuasive empirical evidence for status, trends, and potential impacts is often limited (Panetta and Gooden, 2017). In the Arctic, this resource management challenge is exacerbated by lack of broad-scale monitoring instrumentation and limited agency response capacity given expansive and remote landscapes that are costly to access. All of our case examples show that contributory community-based science projects are especially fruitful if participants are concerned that the phenomenon under study could directly impact their health, food security, or other aspects of their livelihoods. In such cases, contributory citizen science can fill critical information and knowledge gaps at relatively low cost and cover a wide geographic area while only requiring short periods of involvement by participants. These characteristics allow resource managers then to quickly and broadly understand changes and the risk to native ecosystems from invasive species. We recognize that even though the desired management response time is short, resource managers often have a different definition of "quick." Commonly, directed management action occurs about five years after AIS verification. We believe that the availability of data collected through contributory citizen science can further reduce the time span to action. These characteristics enable contributory citizen science programs to fill an important niche in Arctic observing alongside co-created programs.

The relatively fast mobilization of contributory citizen science can also play an important role when local communities have concerns that require immediate data collection due to rapidly changing environmental conditions in the absence of a broad network of instrument-based observing. Food security remains one of the highest concerns for Arctic communities and was a common concern in all three case examples (e.g., salmon, wild berry, and seafood harvesting). When environmental changes occur rapidly and with unanticipated consequences for local communities and economies, scientists should be able to provide readily available data collection protocols deployable across a wide spectrum of public participants. The structured data collection protocol associated with the contributory citizen science approach allows participants to take on a leadership role in their communities even if they are not considered local experts in the natural phenomena being studied. As a result, contributory approaches can recruit a larger and more diverse number of participants where prior knowledge is less critical compared to co-created approaches.

Contributions to Global and International Arctic Observing Networks

Contributory citizen science programs with a demonstrated value to Arctic communities and resource managers are an important component of an international Arctic observing system that has societal benefits. SAON (2018) plays a key role in connecting existing observing efforts and in promoting ethical, free, and open access to the breadth of Arctic observations. However, data from many citizen science programs are not regularly added to global observing programs. Also, many scientists involved in global observing efforts are not fully aware of the availability of citizen-collected data and the utility of citizen science methodologies for collecting information from remote Arctic environments. Thus, it is challenging for SAON to keep an updated inventory of relevant Arctic observing programs that involve local participation. Furthermore, in attempts to connect smaller scale, in situ observations with global observing programs in the Arctic, much emphasis is currently placed on ocean observations (Lee et al., 2019), which leaves a need to build Arctic observing communities of practice around terrestrial and freshwater environments. The case examples presented here provide evidence that Alaska-based contributory citizen science programs can be applied to meet international observing goals, and that in some places, these programs may provide the only localized in situ observations available for monitoring invasive species. The case examples also show that community science data is being incorporated into management decisions at the local level, an exemplary development for international Arctic decision-making bodies that largely underutilize local knowledge and often disregard the desired management outcomes of local and small-scale resource users (Danielsen et al., 2020).

While we do not provide specific recommendations on how to further develop these citizen science programs into an internationally linked network of observations, the SAON initiative may benefit from leveraging existing relationships and common observing interests of local participants and resource managers in the Roadmap for Arctic Observing and Data Systems (ROADS) process (Starkweather et al., 2020).

CONCLUSION

In this article we used three case examples from invasive species management to demonstrate the value of contributory citizen science and CBM for Arctic observing alongside co-created monitoring and science programs. We found that citizen science data collection can be successful in supporting rigorous science, prompting management actions, and being meaningful to communities. Well designed and culturally responsive public participation can not only fill important data gaps but achieve broader societal outcomes by leveraging opportunities for science education, outreach, and environmental stewardship. In contrast to the more established co-created community-based monitoring programs in the Arctic, we view contributory citizen science approaches as an important opportunity to broaden partnerships and co-production of knowledge among scientists, policy makers, and a diversity of Arctic peoples, families, and youth. Broadening and educating the observer base through actionable research will engage and train a new set of future Arctic observers ready to contribute to long-term international observing goals.

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