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Improving sustainability of long-term amphibian monitoring: The value of collaboration and community science for indicator species management

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ABSTRACT

Long-term monitoring is integral to assessing ecological trends, but fluctuations in funding, available resources, and institutional priorities present challenges to the sustainability of monitoring programs. Incorporating community science has the potential to increase the spatial and temporal extent of monitoring efforts while minimizing cost and may be particularly useful for monitoring under-funded species such as amphibians. Concern over the reliability and integrity of data collected by volunteers, however, hampers broader use of community science in ecological monitoring. We assessed the quality of data collected by and the reliability of community scientists participating in a collaborative amphibian monitoring project requiring strict adherence to data collection protocols. Community scientists' ability to correctly identify and detect species was on par with that of professional biologists. Agreement in species detected by community scientists and biologists ranged from 77% to 99% at sites surveyed by both surveyor types in the same season and modeled detection probabilities were similar for all but one species. Follow-through within a season was high. Since 2014, community scientists ($n = 328$) completed 75% of surveys to which they had committed. However, retention of community scientists across years was low, with 81% of participants only involved for one season. Community scientists offset agency resource limitations by conducting 32% of surveys and substantially contributed to meeting sample size goals. Furthermore, although time invested in project management and coordination increased with community science involvement, cost savings from field surveys and centralized coordination offset this increase. Our results suggest that with careful project planning and volunteer training, community scientists can contribute robust data to rigorous scientific studies, but project and participants' goals must align to improve retention across years. Successful programs will require substantial investment by personnel for volunteer recruitment, training, data validation, and dissemination of results, however, involvement of community scientists can improve the sustainability of long-term monitoring programs through collaboration and cost savings. Our results support an increasing body of evidence that community science can contribute significantly to ecological monitoring even when considerable commitment and scientific rigor are essential.

1. Introduction

Long-term ecological monitoring is integral to understanding complex ecosystem and population dynamics (Lindenmayer et al., 2012), assessing ecosystem and biodiversity response to changing climatic conditions or land use practices (Kirby et al., 2007; Magurran et al., 2010), and informing conservation and adaptive management strategies (Havstad and Herrick, 2003; Lindenmayer and Likens, 2009; Eyre et al., 2011). Long-term datasets can provide background information to assess the impacts of management activities (Magurran et al., 2010; Dodds et al., 2012), provide context for other ecological studies (Dodds et al., 2012; Lindenmayer and Likens, 2010), or monitor trends in biological indicators that serve as early-warning systems for declining ecological integrity (Magurran et al., 2010). Although the value of long-term ecological datasets is widely appreciated (Lindenmayer et al., 2012; Magurran et al., 2010; Silvertown et al., 2006; White, 2019), collecting

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and maintaining such datasets can be challenging. Fluctuations in funding, available resources, and institutional priorities are real and often unavoidable challenges to the sustainability of long-term monitoring programs (Allen and Gunderson, 2011; Keith et al., 2011).

Community science, also known as “citizen science,” is a promising approach for sustaining long-term monitoring. Community science is distinguished from traditional research by including non-professional, voluntary participants that collect data to answer scientific questions. Community scientists can enable data collection across larger geographic scales and over longer periods than what is possible in traditional scientific research (Cohn, 2008). Public involvement in scientific research has generated vital datasets used to assess impacts of climate and anthropogenic factors (Miller-Rushing et al., 2012; Cosentino et al., 2014; Weir et al., 2014; Sauer et al., 2017). Community science not only offers a solution for overcoming funding shortfalls and resource limitations that often plague long-term monitoring programs, but also represents an invaluable opportunity to actively engage with the public and increase science literacy.

An impediment to broader use of community science in long-term monitoring is the concern that resulting data are less reliable than data collected by professional scientists (Cohn, 2008) and that challenges with recruitment and retention could negatively affect project longevity. Data collected by volunteers are often viewed with skepticism (Bonney et al., 2014). As a result, scientists must be willing and prepared to systematically scrutinize and filter data. With careful foresight, planning, and protocol development volunteer data rigor can approximate the quality obtained through expert data collection (Danielsen et al., 2005). Volunteer recruitment and retention across years is also a challenge (Cohn, 2008; de Solla et al., 2005; Dickinson et al., 2010; Fitzpatrick et al., 2009; Galloway et al., 2006). Projects should therefore also provide training that allows volunteers to feel confident and capable, offer an experience that is rewarding and enjoyable, be advertised through diverse networks, and remain relevant to interested groups to sustain attention and turnout (Miyoko et al., 2012).

Community science programs may be particularly useful for monitoring under-funded species such as amphibians (e.g., Weir et al., 2014; Petrovan and Schmidt, 2016; Sterrett et al., 2019). Amphibians are often used as indicators of ecosystem function because of their complex life histories that depend on both terrestrial and aquatic ecosystems and their sensitivity to environmental changes and contaminants (Blaustein and Wake, 1990; Welsh and Ollivier, 1998; Pollet and Bendell-Young, 2000; Díaz-García et al., 2017). However, long-term population monitoring is encouraged to separate short-term fluctuations from long-term trends in species that exhibit high inter-annual variability in abundance and reproductive effort, such as observed in amphibians (Blaustein et al., 1994; Green, 1997; Lindenmayer et al., 2012; White, 2019).

Despite the importance of long-term monitoring programs, and the designation of amphibians as indicator species by land management agencies such as the U.S. Forest Service (USFS), sustained long-term amphibian monitoring is uncommon. Limited personnel, annual fluctuations in funding and shifting institutional priorities have created challenges to the establishment of successful long-term amphibian monitoring programs. The Rocky Mountain Amphibian Project (RMAP) was established in 2012 as a multi-agency collaborative effort to monitor amphibians on lands managed for multiple uses. The goal of RMAP is to assess trends in amphibian occupancy over time within the study area. In 2014, we began involving community scientists to improve the sustainability of this long-term monitoring effort. Surveys by community scientists augment those conducted by biologists and biological technicians, improving our ability to survey all sites despite fluctuating resources. Here we assess the reliability of and quality of data collected by community scientists as well as time investment for program management and implementation to evaluate how collaboration and the inclusion of community science data can add to the sustainability of long-term monitoring programs.

2. Materials and methods

2.1. Study area

As of 2021, RMAP encompasses national forest lands in northern Colorado (Routt National Forest), southern Wyoming (Medicine Bow National Forest), and western Wyoming (Bridger-Teton National Forest), USA. The national forests occur in the Rocky Mountains and encompass valleys, meadows, wetlands, conifer forests, and subalpine and alpine areas in portions of at least eight major mountain ranges. Amphibian habitat in the study area includes wet meadows, bogs, beaver ponds, springs, and backwaters or slow-moving areas along mountain streams. Amphibian species include the Western Toad (*Anaxyrus boreas*), Boreal Chorus Frog (*Pseudacris maculata*), and Western Tiger Salamander (*Ambystoma mavortium*). The Northern Leopard Frog (*Lithobates pipiens*) and Wood Frog (*Lithobates sylvaticus*) also occur in northern Colorado and southern Wyoming, and the Columbia Spotted Frog (*Rana luteiventris*) occurs in western Wyoming.

2.2. Field sampling methods

The RMAP study design incorporates U.S. Geological Survey Amphibian Research and Monitoring Initiative (ARMI) guidelines for mid-level occupancy-based monitoring efforts (Corn et al., 2005; Muths et al., 2005), and methods closely resemble those used by monitoring programs in Yellowstone and Grand Teton National Parks (Ray et al., 2021; Bennetts et al., 2013). The primary sampling unit is all aquatic sites within a designated survey area (hereafter “catchment”). A given catchment contains multiple aquatic sites; sites encompass individual wetlands, ponds, wet meadows, bogs, or stream reaches. We used stratified sampling to identify survey catchments in potential amphibian habitat across the study area (Estes-Zumpf et al., 2012; Estes-Zumpf et al., 2014). Currently, 69 established catchments (northern Colorado = 15, southern Wyoming = 18, western Wyoming = 36) encompassing 312 sites are monitored annually. The number of catchments was based on the need to maximize power to detect changes in species occupancy over time (Estes-Zumpf et al., 2012). Catchment size ($\bar{x} = 22.6$ ha) was designed so that all sites within a catchment could be surveyed within one day (one visit) and catchment elevation ranged from 1895 m to 3209 m.

Monitoring of established catchments began in 2012 in southern Wyoming and northern Colorado and in 2014 in western Wyoming, with community science involvement commencing in 2014. Amphibian surveys were conducted during the breeding season (mid-May to early August depending on elevation and annual weather conditions) when species were most detectable. Volunteers were required to monitor in pairs or teams to maximize effectiveness and safety. At least one visit to each of the 69 catchments annually was our target sample size; however, two visits to each catchment each year was encouraged to improve species detection and occupancy estimates. Recruitment of surveyors occurred in three phases each spring. Participating agencies first selected visits to catchments (hereafter “adopted”) based on annual priorities and staffing, then returning community scientists, then all remaining visits to catchments were opened to new community scientists. To maximize sample size and minimize bias in catchments adopted annually, catchments not adopted or those not surveyed by initial adopters were often surveyed by agencies participating in an “as needed” capacity.

Amphibian surveys followed standardized protocols designed to allow estimation of site-level occupancy for each species, after accounting for imperfect detection (MacKenzie et al., 2002). Survey protocols were optimized for implementation by observers with varying levels of biological training. Visual encounter surveys were conducted either independently by each of two observers (dual-observer method; Gould et al., 2012), or collectively by a group of surveyors (team method). Site, survey conditions (e.g., air temperature, cloud cover, precipitation), and species data were recorded separately for each site within a catchment (Muths et al., 2005; Bennetts et al., 2013). Species identified via auditory detection of breeding calls were also recorded. Surveyors recorded evidence of breeding (egg masses, larvae, newly metamorphosed individuals) as well as the number of any adults and juveniles of each species at each site (Muths et al., 2005). For better detection of amphibian larvae, surveyors dip-netted every 5–10 m or in patches of good habitat (quiet inlets/backwater areas or patches of emergent vegetation).

2.3. Data integrity

All surveyors were required to complete annual training. In-person trainings by RMAP project managers or experienced agency biologists consisted of both classroom (2 hr) and field (2 hr) components and taught survey methods, handling, identification (visual and auditory), and decontamination. Online training videos with assessment were available through the RMAP website for surveyors unable to attend an in-person training or for annual recertification. Surveyors then received survey packets including: catchment overview (with basic information, directions, and maps), site-specific datasheets with relevant navigation information and photo points, site maps, and training review information (field guides and protocols for survey, handling, and decontamination).

To validate species identification, surveyors were instructed to photograph at least one individual of each species detected at each catchment, collect and submit 1–3 individuals from tadpole groups (preserved in ethanol) to RMAP program managers, and photograph amphibians or egg masses they were unable to positively identify in the field, when possible. Following surveys, data were entered online by the surveyors or submitted to RMAP project managers for entry, with datasheets (hardcopies or scanned) submitted for data vetting. Records were flagged as low quality (i.e., managers had low confidence in species identification) if: 1) the observer noted a poor visual observation of an animal, 2) associated data (photo or tadpole specimen) demonstrated incorrect field identification, 3) a single unverified species record occurred at a catchment, or 4) an unverified record occurred outside the species known range.

2.4. Community scientist participation, follow-through and retention

We determined the number of community scientists who participated in RMAP by number of surveyors reported on datasheets. Follow-through was defined as the probability that community scientists conducted surveys at their adopted catchments and was calculated as the number of catchment visits completed divided by the number of visits adopted by community scientists each year (excluding surveys prevented due to road closures and wildfire ($n = 3$)). Volunteer retention was defined as the probability that volunteers conducted surveys for more than one year. We assessed retention by tallying the number of years each individual or organization (e.g., youth corps, Boy Scout troops) conducted surveys. The number of years individuals participated is conservative, as full names of all participants were not always provided.

2.5. Assessing species identification and detection by community scientists and biologists

We examined the ability of community scientists to correctly identify amphibians by determining the proportion of low confidence species records submitted across community scientists. To compare species detection between community scientists and biologists, we examined results from catchments surveyed by biologists and community scientists during the same breeding season but on separate visits. We did not assume data from biologists represented truth (i.e., perfect species identification and detection). We first compared species reported by each surveyor type for each site within a year by calculating percent agreement between surveyor types and Cohen's kappa (κ; range: -1 to $+1$ where $0 =$ random and $1 =$ perfect agreement) after excluding low confidence observations (e.g., data filtering). We visualized results in agreement matrices. This provides a site-by-site paired comparison of species recorded by each surveyor type to determine how often data for each site was corroborated by both surveyor types and where differences occurred.

The overarching goal of RMAP is to assess trends in amphibian occupancy and higher detection probabilities lead to more precise occupancy estimates (MacKenzie et al., 2002). To assess differences in detection probability by surveyor type, we modeled probability of species detection by community scientists and biologists after accounting for the influence of environmental variables, timing of surveys, and probability of occupancy. This analysis assesses overall ability of each surveyor type to detect a species when present, and differs from the agreement analysis in that it does not provide a direct comparison of site-specific results between surveyor types. We used the final (filtered) dataset (above) of sites surveyed by both community scientists and biologists during the same breeding season and excluded all records considered low confidence. Because our objective was to compare detection, we used this paired subset of data to ensure an equal sample size by surveyor type and we considered data from each year independent ($n = 274$). Most sites that met this paired surveyor type criterion did so for a single year; therefore, we used single-season occupancy models to estimate detection probabilities (MacKenzie et al., 2002) by species in RMark (Laake, 2013), an R implementation of Program MARK (White and Burnham, 1999). In single-season models, occupancy probability ψ_i is the probability that a site i is occupied by a target species, and detection probability p_{ij} is the probability of detecting the species at site i in survey j, given the site is occupied (MacKenzie et al., 2002). Single-season occupancy models assume no false positives (species was recorded present when absent) and site occupancy does not change between surveys.

To account for differences in occupancy while estimating detection, we used a two-stage modeling approach to assess the effect of surveyor type on detection probability. We verified this approach in a supplemental analysis in which we modeled detection and occupancy simultaneously (see below). First, we determined an optimal occupancy model while holding detection probabilities constant. Occupancy was modeled as constant (intercept-only), variable by year, variable by percent emergent vegetation, or an additive combination of year and percent emergent vegetation, resulting in four candidate models of occupancy. To account for any confounding effects of vegetation on both occupancy and detection (Gould et al., 2012; Swartz et al., 2020), we included percent emergent vegetation as a site-level covariate (percent shoreline with emergent vegetation ($\geq$50% or $<$ 50%) at first survey visit of each season). We removed 2018 data from analyses for four of the six species (Columbia Spotted Frogs, Northern Leopard Frogs, Tiger Salamanders, and Wood Frogs) as low sample size (paired data for only 13 sites) and few detections at those sites prevented certain models from converging. Although ecologically-based occupancy models will ultimately be used to assess trends in species occupancy across the study area, occupancy trends will be estimated using the full dataset (all years and sites) and is beyond the scope of this paper.

We next tested competing models of detection with occupancy parameterized according to the top model for each species (see Results). To test for effects of surveyor attributes on detection probability, we included surveyor type (community scientist/biologist) and number of observers as predictor variables. We also tested for effects of several ecological covariates on detection (see Table 1), as well as constant (intercept-only) and time-varying detection (by year). The candidate model set included all possible additive combinations of surveyor type, number of observers, Julian date, percent margin vegetation and site area. We also included a 'day conditions' model with air temperature, air temperature (quadratic), survey start hour, cloud cover, and wind.

Table 1
Predictor variables used to model occupancy (ψ) and detection probabilities (p) for six amphibian species on the Medicine Bow National Forest in southern Wyoming, Routt National Forest in northern Colorado, and Bridger-Teton National Forest in western Wyoming.

Predictor	Parameter	Description
airtemp	p	air temperature (°C)
area	p	area (ha) of surveyed site
surveyor	p	survey conducted by community scientist or biologist
cloud	p	clear (≤25% clouds) or overcast (>25% clouds)
jdate	p	Julian date
observers	p	number of observers
starthr	p	start hour of survey
tempsq	p	quadratic effect of air temperature (°C)
veg	p, ψ	percent margin vegetation ≤ 50% or > 50% *
wind	p	calm or moderate/strong winds
year	p, ψ	survey year (2014–2019)

*for p, veg was assessed during each survey; for ψ, veg was assessed during the first visit of the season

We screened predictor variables for collinearity using Pearson's correlation coefficient (Pearson, 1895); no pairwise correlations were > 0.4 and all variables were retained in the analysis (Dormann et al., 2013). Model selection was based on adjusted Akaike's information criterion (AICc; Akaike, 1973) and models (occupancy: n = 4, detection: n = 39) were ranked by second-order AICc differences (ΔAICc; Burnham and Anderson, 2002). AICc weights were used to compare the relative support for each model (Buckland et al., 1997).

A two-stage modeling approach to identify top detection and occupancy models is commonly used to simplify and reduce the number of competing models. Although we acknowledge that our approach of parameterizing occupancy first is unconventional, we believe it statistically valid. To confirm the validity of this approach, we also modeled detection and occupancy simultaneously, resulting in 156 candidate models for each species, and compared whether the same top occupancy models were identified using both approaches.

We calculated parameter estimates of detection probabilities for community scientists and biologists separately (covariate.predictions, RMark, Laake, 2013). These estimates were averaged across all candidate models (n = 39) while holding all other parameters at mean values and weighted by AIC model weights to account for model uncertainty (Cooch and White, 2007). Non-overlapping confidence intervals surrounding detection estimates were considered evidence of differences in detection probabilities between community scientists and biologists.

2.6. *Assessing sustainability*

Annual surveys from established catchments are necessary to monitor trends in occupancy. Insufficient data can decrease confidence around occupancy estimates or prevent estimating occupancy for some regions in some years. To assess whether or not RMAP met the target sample size of at least one visit to each catchment in each region, we determined the percentage of all catchments in each region that were surveyed in a given year and the percentage of catchments surveyed by the different surveyor types (community scientist or biologist). We also determined the percentage of catchments receiving a single visit versus the optimal two visits during a breeding season. Relative contributions were averaged over 2014–2019. Catchments that were surveyed by both surveyor types in the same year (either on different visits or working together) were categorized as such.

To evaluate how collaboration with community scientists influenced the financial sustainability of the program, we compared the average personnel time currently invested annually by state and federal agency partners when community scientist are involved to the predicted time investment necessary to complete the same amount of work without community scientist involvement. Program start-up costs (e.g., web development, study design, survey material preparation, etc.,) and equipment and supplies costs were not included in analyses. Because number of observers per survey can vary substantially if large groups participate (e.g., Boy Scouts) time estimates for surveys were calculated for a simple dual-observer study design (i.e., two observers/catchment visit). To standardize personnel cost across all collaborators, we used the United States Office of Personnel Management General Schedule (GS) pay scale by Grade and Step (USOPM, 2021) and assigned GS ranks based on experience level and training required to hold that position title (e.g., wildlife biologist = GS11 regardless of agency/institution; Levrel et al., 2010). Fringe was estimated at 15% for seasonal employees (here GS5 and GS6) and 40% for permanent employees (GS11 and GS13; USFS Human Resources, Personal communication). Regional program managers provided estimates of average annual time investment by personnel according to GS rank.

3. Results

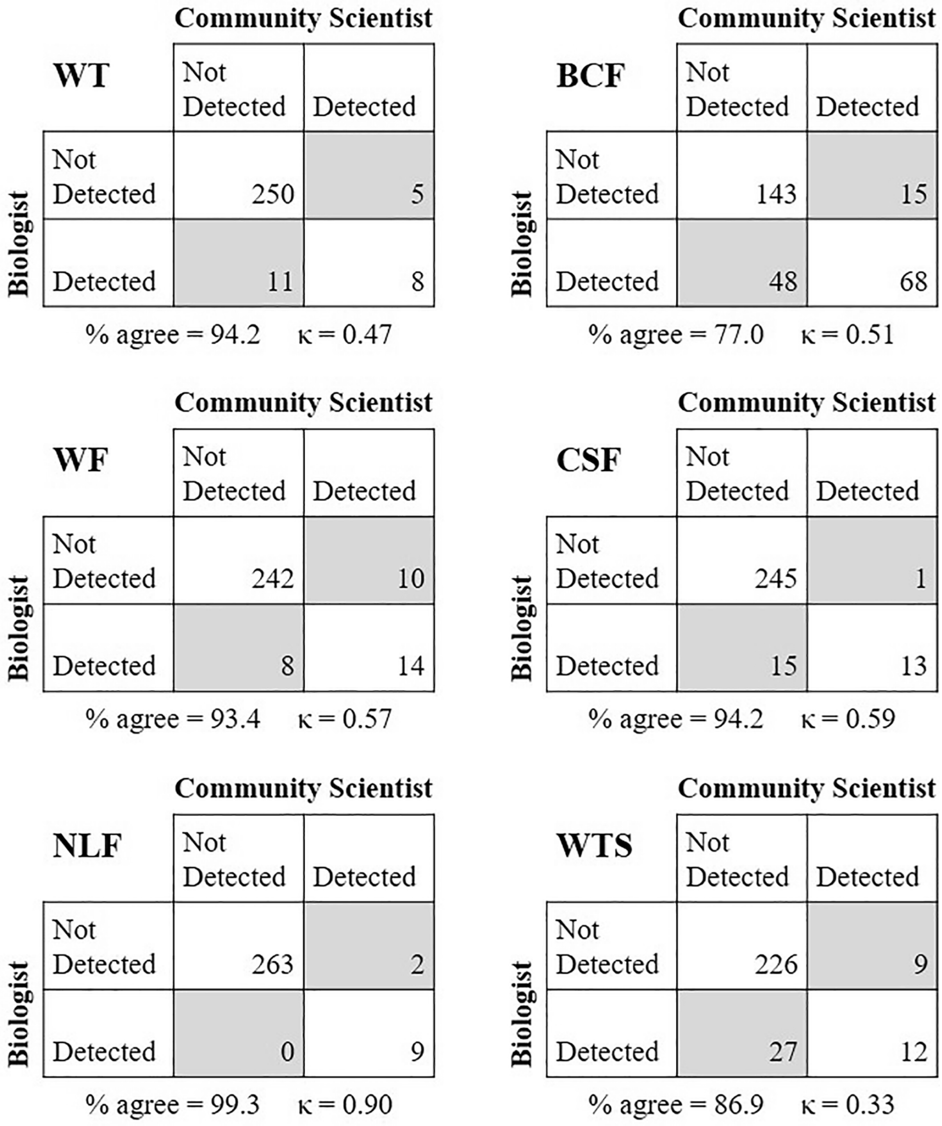
3.1. *Community scientist participation, follow-through, and retention*

A total of 328 ($\bar{x}$ = 72/yr) community scientists participated in RMAP between 2014 and 2019 with a majority as individuals, but some as part of a formal group (Boy Scout troops, Rocky Mountain Youth Corps, Wyoming Conservation Corps, discovery camps, church groups). Community scientists contributed a minimum of 615 days in the field and hiked over 1710 km. From 2014 to 2019, community scientists adopted 250 surveys at 54 catchments and completed 75% of those surveys with follow-through higher for first visits to a catchment (83%) than for second visits (64%) within a season. Retention of community scientists was low with only 19% of individuals or groups participating for more than one year. Only 4% of community scientists volunteered for four or more years.

3.2. *Species identification and detection*

Community scientists submitted 557 species records, 71 (12.7%) of which had accompanying photographs or tadpole samples for verification. Of all records submitted, 25 (4.5%) were flagged as low confidence due to questionable data (3.1%) or because records were first occurrences without accompanying photos for confirmation (1.4%). Of the 274 instances where a site was surveyed by both surveyor types in the same breeding season, agreement between community scientists and biologists ranged from 77% to 99% and was lowest for Boreal Chorus Frogs and highest for Northern Leopard Frogs (white diagonals, Fig. 1). Cohen's kappa scores ranged from 0.33 to 0.90, indicating moderate or substantial agreement between surveyor types for all species other than the Western Tiger Salamander. Disagreement (gray diagonals, Fig. 1) among surveyor types was generally low except for Boreal Chorus Frogs and Western Tiger Salamanders, though biologists also detected more Columbia Spotted Frogs than community scientists.

To compare estimated detection probabilities between surveyor types, we first had to control for differences in occupancy across sites. As it was not our goal to generate ecologically interpretable occupancy estimates but instead to control for differences in occupancy biasing detection estimates, we do not discuss occupancy results (see Tables S1-S5 for details). Model averaged estimates of detection probabilities were comparable between biologists and community scientists for most species, differing only for Boreal Chorus Frogs, where detection probability was higher for biologists (p = 0.74, 95% CI = 0.69–0.79) than for community scientists (p = 0.44, 95% CI = 0.37–0.50; Fig. 2). Data were too sparse to model detection for Northern Leopard Frogs. Top detection models differed among species and included different suites of ecological and surveyor predictor variables but were characterized by high uncertainty for all species (4–14 models per species with ΔAICc < 2; Appendix A, Tables S1-S5), justifying our approach to generate model averaged estimates of detection across all candidate models. Notably, all top detection models for Boreal Chorus Frogs (eight models had ΔAICc



WT (Biologist \ Community Scientist)	Not Detected	Detected
Not Detected	250	5
Detected	11	8

% agree = 94.2 κ = 0.47

BCF (Biologist \ Community Scientist)	Not Detected	Detected
Not Detected	143	15
Detected	48	68

% agree = 77.0 κ = 0.51

WF (Biologist \ Community Scientist)	Not Detected	Detected
Not Detected	242	10
Detected	8	14

% agree = 93.4 κ = 0.57

CSF (Biologist \ Community Scientist)	Not Detected	Detected
Not Detected	245	1
Detected	15	13

% agree = 94.2 κ = 0.59

NLF (Biologist \ Community Scientist)	Not Detected	Detected
Not Detected	263	2
Detected	0	9

% agree = 99.3 κ = 0.90

WTS (Biologist \ Community Scientist)	Not Detected	Detected
Not Detected	226	9
Detected	27	12

% agree = 86.9 κ = 0.33

Fig. 1. Agreement matrices between biologist and community scientists for six amphibian species (Western Toad (*Anaxyrus boreas*; WT), Boreal Chorus Frog (*Pseudacris maculata*; BCF), Wood Frog (*Lithobates sylvatics*; WF), Columbia Spotted Frog (*Rana luteiventris*; CSF), Northern Leopard Frog (*Lithobates pipiens*; NLF), and Western Tiger Salamander (*Ambystoma mavortium*; WTS)). Species detection results were summarized for all instances where both surveyor types surveyed the same site independently during the same breeding season ($n = 274$). Agreements between surveyor types are on the white diagonals while disagreements are on the gray diagonals. Percent agreement and Cohen's Kappa for each species are presented below the respective matrix. Cohen's kappa values above 0 indicate agreement is better than random chance and $\kappa = 1$ represents perfect agreement.

< 2) included number of observers (Appendix A, Table S1), and indicated detection probability increased with number of observers (top model beta = 0.51, 95% = 0.29–0.72; Fig. 3). Models with number of observers were not consistently highly ranked for any of the other species (Appendix A, Tables S2-S5). Modeling occupancy and detection simultaneously identified the same top occupancy model for all study species except Wood Frogs, where a second model had roughly equal support (Tables S6-S10).

3.3. Sustainability

The relative contribution of community scientists and biologists to meeting sample size goals (at least one visit to each catchment each year) varied among years and across regions (Fig. 4). Across the study area, 91.2% of catchments ($n = 63$) were surveyed at least once and 66.7% of catchments ($n = 46$) were surveyed at least twice each year for an average of 109 catchment visits annually. RMAP relied on community scientists the most to complete surveys in southern Wyoming, while agency biologists conducted most surveys in northern Colorado. Western Wyoming has the most remote catchments, including six wilderness catchments, some of which require overnight backpacking to survey. Although each was occasionally surveyed, not all remote catchments were surveyed annually and they account for the higher average rate of catchments not surveyed ($\bar{x} = 17\%$) in that region (Fig. 4).

To evaluate how involvement of community scientists influenced fiscal sustainability, we estimated the number of personnel hours necessary to implement RMAP monitoring at the current level of effort ($n = 109$ catchment visits/year). Current project personnel time was allocated based on the current rate of community science involvement (31.5% of visits across all regions; Table 2). Time required for program management and coordination was greater when community scientists were involved (Table 2). We estimated that net time investment by GS6 and GS11 program managers increased 320 and 60 hrs, respectively, with community scientist involvement (Table 3). This was largely due to a four-month part-time GS6 project coordinator hired annually to assist biologists with community scientist coordination and overall data management and report writing. Despite increased time invested in project management, community scientists saved agencies 594 h of GS5 time for field surveys and data entry. This resulted in a net savings across all GS ranks of $2,011 when community scientists participated in RMAP (Table 3).

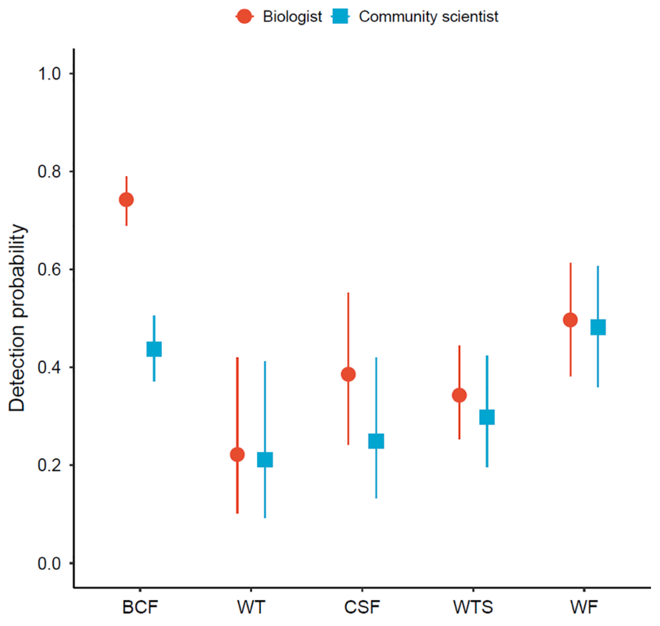


Fig. 2. Estimated detection probabilities for five amphibian species in southern and western Wyoming and northern Colorado. Predictions for biologists (red) and community scientists (blue) with 95% confidence intervals are model averaged over all candidate models while holding other covariates at mean values. BCF = Boreal Chorus Frog; WT = Western Toad; CSF = Columbia Spotted Frog; WTS = Western Tiger Salamander; WF = Wood Frog. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

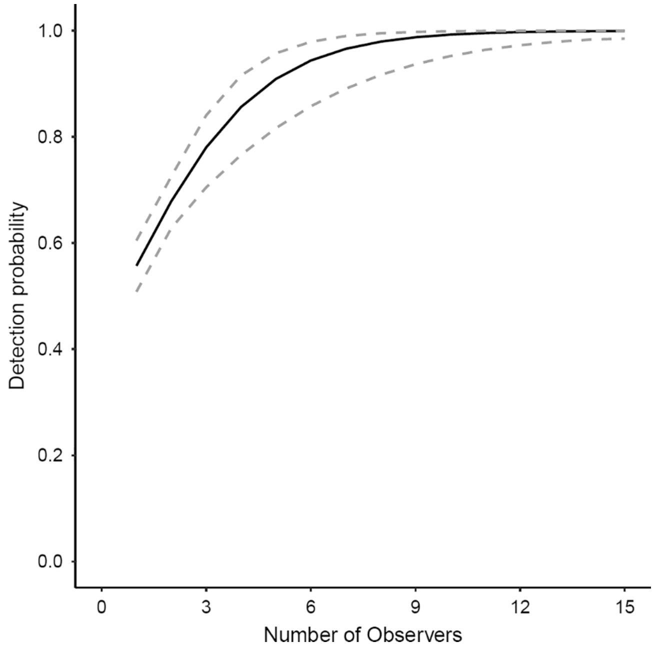


Fig. 3. Predicted detection probabilities as a function of number of observers for Boreal Chorus Frogs in southern and western Wyoming and northern Colorado. The black solid line is the predicted mean model-averaged across all candidate detection models while holding all other covariates at mean values. Dotted gray lines indicate 95% confidence intervals around the predicted mean.

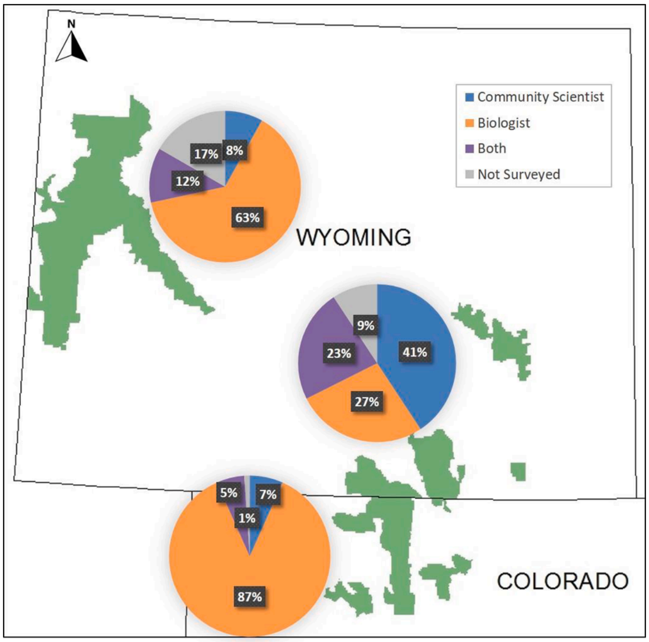


Fig. 4. Relative contribution of community scientists and biologists (averaged over 2014–2019) to monitoring catchments on national forest lands (shaded in green) in western Wyoming (n = 36), southern Wyoming (n = 18), and Colorado (n = 15). Catchments that were surveyed by both surveyor types in the same year (either on different visits or working together) were categorized as "both". (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4. Discussion

Sustaining long-term ecological monitoring programs is challenging and incorporating community science has the potential to increase the spatial and temporal extent of monitoring efforts while minimizing cost. In addition, including community scientists has broader potential benefits including increasing science literacy and overall engagement in the natural world (Conrad and Hilchey, 2011; Bonney et al., 2014). Rigorous design-based programs depend on strict adherence to data collection protocols to produce high quality data. While these non-opportunistic data collection ventures more accurately model science, they require substantial investment and commitment from community scientists. A critical need in community science approaches is to assess the quality of information gathered from community scientists relative to professional scientists.

The involvement of both biologists and community scientists in RMAP presents a unique opportunity to assess the overall viability of a community science effort for long-term monitoring of a suite of indicator species. We found that community scientists contributed data comparable to that of biologists for most species and could be relied on to follow-through with data collection even under physically demanding conditions. Community scientist involvement was critical to reaching sample sizes goals needed for trend analyses using data-intensive models. However, multi-year commitments from the same community scientists were rare, requiring on-going recruitment and training efforts. Successful programs will require substantial planning and investment upfront; however, involvement of community scientists can improve the sustainability of long-term monitoring programs through collaboration and cost savings.

We found community scientists proved highly capable of detecting and correctly identifying focal amphibian species. Only 4.5% of observations were flagged as having low confidence in species identification, with a portion of those due to lack of confirmatory information. We found moderate to substantial agreement between biologists and community scientists in species reported at sites, despite differences in survey day and conditions (Fig. 1). Agreement was highest for Northern Leopard Frogs, a large and relatively easy-to-identify species that is often abundant at a site when present. The least agreement between

Table 2

Estimated personnel time (in hours) for implementing Rocky Mountain Amphibian Project annual monitoring efforts at an average survey effort of 109 catchment visits/year. Total annual time investment by United States Office of Personnel Management General Schedule (GS) pay rank (USOPM, 2021) was estimated for the current project (community scientists (CS) conduct 31.5% of surveys and biological technicians (Bio) conduct 68.5% of surveys annually) and for the same project conducted by state and federal agency partners without community scientist involvement.

	Field surveys (GS5)		Data entry[a] (GS5)		Data vetting		Trainings	Project coordination		Database management[d]	Database & web interface oversight	Statistical analyses	Reporting[e]	
	CS	Bio	CS	Bio	GS6	GS11	GS11	GS6	GS11	GS11	GS13	GS13	GS6	GS11
Current investment with community scientist involvement	549	1195	45	97	64[b]	16	92[c]	216	320	88	8	80	40	24
Projected agency investment without community scientists		1744		142		40	32		296	72	8	80		40

[a] Data entry estimated at 1.3 h/catchment visit.

[b] Includes additional data vetting/entry time for when volunteers had difficulty entering data online (more users learning the data entry tool = more errors).

[c] In addition to group trainings by agency biologists for seasonal technicians, includes training days and travel by project manager for four in-person trainings held for community scientists, "after class" training on how to use a GPS unit, and training of the part-time coordinator by the project manager.

[d] Final data vetting, formatting, uploading

[e] Additional reporting required for grants to support the part-time coordinator position.

Table 3

Net costs to state and federal agency partners for implementing Rocky Mountain Amphibian Project annual monitoring efforts with and without the current level of community science involvement. Personnel hours and rate of pay are allocated based on United States Office of Personnel Management General Schedule (GS) hourly rates by Grade and Scale for 2021 (USOPM, 2021) plus fringe estimated at 15% for seasonal employees (here GS5 and GS6) and 40% for permanent employees (GS11 and GS13). A negative value indicates costs not incurred (i.e., cost savings) by agency partners.

GS Rank	Current agency investment with Community Scientists	Projected agency investment without community scientists	Net hours	Hourly Rate	Total Net Cost
GS5	1292	1886	-594	$19.44	-$11547
GS6	320	0	320	$21.67	$6934
GS11	540	480	60	$43.37	$2602
GS13	88	88	0	$44.15	$0
Cost Savings					**-$2011**

surveyor types occurred for Western Tiger Salamanders, which are primarily detected via dip netting for larvae as terrestrial adults typically leave ponds after breeding. Although the rate of disagreement was low for Columbia Spotted Frogs (5.8%), biologists detected notably more individuals than community scientists. These results were partly due to biologists detecting tadpoles of this relatively rare species more often than did community scientists. Overall, these results are encouraging, but suggest that reliably detecting more cryptic species may require additional training.

Community scientists detected species at similar rates to biologists (Fig. 2), suggesting community science data are a valuable and combining surveyor types does not introduce bias. Detection probability was higher for biologists than community scientists for Boreal Chorus Frogs, the smallest amphibian in our study area (~3.8 cm snout-vent) and more easily detected by their distinctive call rather than visually. Although community scientists were trained to recognize calls, less experienced surveyors may not notice calls while concentrating on visual searches. In addition, the small size may influence detection probability, supported by a significant positive relationship between Boreal Chorus Frog detection probability and number of observers. The number of observers was greater for community scientists (range: 1–15; $\overline{x} = 2.20$) than biologists (range: 1–6; $\overline{x} = 1.06$). Increasing observer group size can help to offset lower detection rates of community scientists for this species (Fig. 3). However, both ecological and observer covariates influenced detection probability (see Appendix A, Tables S1-S5), suggesting that habitat characteristics and weather conditions have an equal or stronger influence on detectability than surveyor type for most species. Although we modeled observer type as a simple fixed effect, occupancy models are powerful analytical tools for similar collaborative studies as they can control for heterogeneity in observers as quantified across a range of metrics (e.g., level of experience, years of participation, assessment test scores). However, improving surveyor skills rather than simply controlling for observer variation also increases the robustness of results. For RMAP and similar projects, increased emphasis during training on learning and actively listening for specific amphibian calls and on dip netting for larvae could improve detection of cryptic species and lifeforms. Supplementing visual surveys with environmental DNA (eDNA) collection can also improve detection of rare and cryptic species (Gygli, 2017) and may help overcome detection discrepancies between community scientists and biologists for Boreal Chorus Frogs and Wester Tiger Salamanders.

Long-term monitoring is critical for assessing indicator population trends, especially in species that exhibit high inter-annual variability in abundance and reproductive effort (Blaustein et al., 1994; Green, 1997; White, 2019), but annual and regional variation in funding, resources, and institutional priorities threaten sustainability. While biologists conducted the majority of surveys, sample size goals were met within each region in most years through collaboration with community scientists. On average, community scientists conducted one or both surveys at 32% of catchments across the three study regions, substantially contributing to meeting sample size goals in both southern and western Wyoming. Annual coordination among all stakeholders facilitated matching community science resources with fluctuating agency capacity and minimizing bias in catchments surveyed annually. Bias in catchment selection among surveyor types is minimal; both biologists and community scientists surveyed catchments across a range of difficulty levels.

In many cases, agencies adopted one visit to catchments in their region and the second visit was available for adoption by community scientists. Catchment difficulty can influence retention for some community scientists, but others specifically choose and return to difficult catchments. Species detection also likely influences retention for some community scientists, with lower retention of volunteers between years at species-poor catchments. To reduce bias in catchment selection and species detection, results from previous surveys are not readily available prior to catchment adoption.

Participation in RMAP requires considerable effort and commitment. Collectively, community scientists hiked over 1710 km, much of it off-trail across mountainous terrain. Despite this challenge, 75% percent of participants completed their adopted surveys, with follow-through higher for first visits to a catchment (83%) than for second visits (64%), suggesting that commitment wanes after community scientists complete what they may perceive as their minimum commitment. Although initial follow-through was high, we found little retention of community scientists across years. The majority of participants (81%) were only involved for one season. This high turnover rate suggests that community scientists either gain what they wanted from the experience in one year or that rewards gained from participating are not worth the effort invested. The high turnover rate of RMAP volunteers is echoed in other community science projects (Frensley et al., 2017; Reyna and Rollins, 2017) and may stem from the perceived difficulty of tasks asked of volunteers (Delaney et al., 2008), the time commitment required to participate in the project, or because the motivations of volunteers to join the project did not align with the project's goals (Reyna and Rollins, 2017). Furthermore, delays in annual summaries regarding project achievements and in analyzing and reporting occupancy trends could cause participants to doubt the significance of their contributions. Timely analysis and dissemination of results is critical to retaining community scientists as well as partners. Technology that allows for cloud-based data collection with smartphones or tablets paired with well-designed online results portals could allow participants to view their contributions in real-time when formal analyses are not immediately forthcoming. Increasing volunteer retention could increase the quality of data contributed as surveyors gain experience with the project (Kosmala et al., 2016), thereby reducing training and data validation demands required of program managers and increasing overall sustainability of the program. Assessing community scientists' motivations for participating and reasons for continuing or discontinuing participation as well as aligning project and participant goals also could improve retention.

Data quality, contributor reliability and long-term success of community science programs will vary depending on the community scientists attracted to a program. Community science projects tend to attract a highly educated demographic with interests in wildlife and the environment (Trumbull et al., 2000), and university partnerships could enhance recruitment. RMAP recruits a high proportion of professionals in STEM (science, technology, engineering and mathematics) fields. Approximately 45% of RMAP volunteers over 18 years of age are professional scientists or students and therefore likely familiar with the scientific method and data collection. Many RMAP volunteers also participate in other community science projects through the University of Wyoming Biodiversity Institute (BI). About 36% of BI volunteers who responded to surveys (n = 93) have a post-graduate degree and about 36% have a bachelor's degree as their highest degree earned. However, the type of training volunteers receive influences their ability to collect accurate data more than education level (Ratnieks et al., 2016). Both the demographics of RMAP volunteers and the structured training required for all participants likely contributed to the high quality of data collected, but the time required for intensive training and data vetting by program managers can impact the sustainability of similar monitoring efforts.

Community science is often viewed as a reduced-cost means of collecting scientific data. Although this may be the case for programs based on 'crowdsourcing' opportunistic observations (e.g., ebird (Sullivan et al., 2009), iNaturalist (https://www.inaturalist.org)), cost savings for projects that require considerable surveyor training, detailed data collection, and data management and analysis could vary depending on how project management is structured. Maintaining the integrity of RMAP data requires considerable effort from agency and institutional partners. However, we found that despite greater time investment necessary for project management and coordination when community scientists were involved (Table 2), savings from work conducted by community scientists as well as through the hiring of a seasonal coordinator more than offset project management costs. Key to this offset was that much of the time invested in project management that normally would fall to permanent biologists from partnering agencies in the absence of community science involvement was instead consolidated under the part-time GS6-level project coordinator. Funding for this centralized coordination was largely available through grants awarded because the position supported community science and promoted science literacy. Of note is that although we demonstrate that cost savings for implementation of rigorous design-based community science projects is possible, substantial initial funding typically is needed to develop easy-to-follow protocols, training resources, accessible data entry portals, and a well-designed database. Though such costs are inherent in any designed-based monitoring program, involving participants from diverse backgrounds often requires additional time and skills to develop resources that will minimize bias due to variation in participants' prior knowledge of scientific data collection (Danielsen et al., 2005; Cohn, 2008; Dickinson et al., 2010).

Community science has a long history of contributing to monitoring efforts (Miller-Rushing et al., 2012), but data collected by community scientists are often viewed as less reliable than that of professional scientists (Cohn, 2008; Bonney et al., 2014). With careful project planning, protocol development, and volunteer training, community scientists can contribute robust data to rigorous scientific studies. Furthermore, advances in technology can improve data integrity, such as through controls on accepted values in structured data submission portals, broadly accessible training resources, and data validation algorithms, thereby enabling successful implementation of study designs (Dickinson et al., 2010; Crall et al., 2011; Bonney et al., 2014; Kosmala et al., 2016). We believe incorporating community science represents a viable solution for overcoming fluctuating resource limitations that often plague long-term monitoring efforts, but emphasize that successful programs will still require considerable investment by program managers and other professionals. Our results support an increasing body of evidence that community science can contribute significantly to monitoring ecological indicators even when considerable commitment and scientific rigor is essential.

CRediT authorship contribution statement

Wendy Estes-Zumpf: Conceptualization, Project administration, Data curation, Writing – original draft. **Brett Addis:** Formal analysis, Writing – original draft. **Brenna Marsicek:** Conceptualization, Project administration, Resources, Writing – original draft. **Mason Lee:** Project administration, Writing – original draft. **Zoe Nelson:** Project administration, Writing – original draft. **Melanie Murphy:** Supervision, Writing – original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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