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Using local ecological knowledge as evidence to guide management: A community-led harvest calculator for muskoxen in Greenland

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Abstract

Indigenous people manage or have tenure rights on over a quarter of the world's land surface. While there is growing interest in "evidence-based" natural resource management, there are few documented experiences with "evidence-based" practice in community-managed lands. We explore the evidence required for decisions about harvesting of a community-managed muskox herd in Greenland, and the collaboration needed to acquire this evidence. We present the development, application, and outcome of a user-friendly demographic model—a harvest calculator—and we show how Local Ecological Knowledge was used throughout the process and combined with scientific knowledge. The community members identified suitable harvest scenarios with the use of the calculator. The calculator's predictions corresponded with their own perceptions of declining numbers of muskox bulls and suggested that reversal was possible under an alternative harvest scenario. As a result, the community members used the findings to request a revised muskox harvest quota, which gained immediate approval by the government. We draw on our experience to propose where community-led harvest calculators can be useful. Community-led harvest calculators can help indigenous and local communities develop economically within environmentally sustainable limits, while at the same time providing community members a "voice" in natural resource governance. An effective local management regime will require the sustained application of this tool.

KEYWORDS
Aichi Target 18, harvest, indigenous, local ecological knowledge

1 | INTRODUCTION

"Evidence-based" practice in natural resource management is receiving growing interest (Sutherland & Wordley, 2018). How to appropriately use available evidence in a given conservation situation is not necessarily a straightforward task (Salafsky et al., 2019). In evidence-based practice, "*rather than merely relying on personal* *experience or anecdote, practitioners make decisions and take actions that are informed by systematic and critical analyses of both their own and the world's previous experiences*" (Ibid., 2).

Evidence-based practice is particularly challenging for community-managed wildlife resources, as they are often found in remote areas where surveys are logistically demanding and financial resources limited (Danielsen, et al., 2020). Here, we consider what evidence is needed to make decisions in such situations and how, through collaboration between community members and external stakeholders, the necessary evidence can be compiled.

Countries that ratified the Convention on Biological Diversity are obliged to respect, preserve, and maintain knowledge of indigenous and local communities, and have agreed to achieve a set of goals, that is, Aichi Targets, by 2020 (UNEP, 2012). The Target-18 strategic goal includes that indigenous and local knowledge should be "fully integrated and reflected in the implementation of the Convention" by 2020. A key challenge is how to connect information generated by different knowledge systems for informing management (Game et al., 2018; Tengö et al., 2017; Tomaselli, Kutz, Gerlach, & Checkley, 2018). Indigenous people have rights to or manage at least 37.9 million km^2 of land from the tropics to the poles (Garnett, Burgess, Fa, Leiper, et al., 2018). However, current science-based land management systems may not be able to effectively include indigenous and local perspectives (Tengö, Austin, et al., In review; Dallman, Peskov, Murashko, & Khmeleva, 2011).

The climate is changing and the people in the Arctic are facing huge challenges. Many rely on natural resources for both subsistence and income. The Arctic socio-ecological systems are undergoing transformational, rapid changes that exceed those in other regions in magnitude (Eicken et al., In review). As a result, there is pressing need to effectively use all available knowledge to cope with and adapt to these changes.

In Greenland, muskoxen (*Ovibos moschatus*) are an important source of meat and income to Inuit and other communities, particularly in small, remote settlements with few alternative income sources. Fjords and glacial tongues of ice separate regional sub-populations of muskoxen. There is limited understanding of the status of most of the sub-populations and the government has minimal ability to undertake population assessments. Therefore, it is difficult for Greenland's Ministry of Fisheries, Hunting and Agriculture to optimally manage each sub-population.

One solution proposed by the Greenland Government is to hand over a larger share of the responsibility for managing muskox sub-populations to the local users. The government is co-developing and testing strategies and tools together with communities for incorporating Local Ecological Knowledge (LEK) into decision-making on the management of muskoxen (Mistry & Berardi, 2016). As part of this effort, we investigated a collaborative community-government approach whereby a muskox demographic model based on the community-members' own observations and knowledge was used to predict future muskox abundance, which in turn informed government decisions regarding harvest management.

In this paper, we describe the development, application, and outcome of the model and how LEK and scientific knowledge were documented and used. For convenience, we call the model a "harvest calculator." Our study focused on a small (ca. 1,000) translocated muskox sub-population in the Ivittuut region, southwest Greenland. The Ivittuut region is an important hunting area, which is just 10 km from the indigenous community of Arsuk. Deep fjords and the Greenland Ice Cap bound the ~430 km^2 region. Vegetation is tundra with elevation ranging from sea level to over 1,000 m. In 1987, the Ivittuut Municipality moved 15 juvenile muskoxen to the Ivittuut region to enable future hunting for meat and trophies. Since 1998, community members monitored sub-population abundance. In recent years, the community members have become concerned about the sustainability of their commercially valuable guided trophy-hunt. Arsuk has 67 inhabitants, down from a peak population of approximately 400. The economy had previously been supported through a cod (*Gadus morhua*) fishery, which has declined significantly in recent years. As a result, there is considerable interest in finding alternative sources of economic activity in the community. Arsuk is the only settlement near the Ivittuut muskox herd and thus has had the most direct impact on the management of the Ivittuut region. From Arsuk, the Ivittuut region can be reached in half an hour, whereas from other settlements, it requires at least 3 hr of travel by boat.

While private landowners and protected area managers frequently use ecological models when managing populations of big game (Caro, Young, Cauldwell, & Brown, 2009), we know of only few examples where community members have used ecological models for guiding decision-making in community-managed areas (Nesbitt & Adamczewski, 2009; Porcupine Caribou Management Board, 2010). Typically, such models predict changing size and structure of a population over time in response to assumptions regarding processes including recruitment, natural mortality, and harvest (Ellner & Guckenheimer, 2006). Moreover, scientists use models to forecast sustainable yields (e.g., fisheries), extinction risk of threatened species, potential consequences of biological invasions, and spread of parasites, viruses, and disease (Morris & Doak, 2002; Tuljapurkar & Caswell, 1997). The literature on mathematical modeling involving local stakeholders ("participatory modeling") refers to models of social and ecological systems, which incorporate biological, physical, socio-economic, and behavioral factors (Voinov et al., 2016); however, these require professional modelers to run them. In contrast, we speculated whether demographically simple ecological models, involving community members' own observations and knowledge, could be used by community members themselves in community-managed areas, and whether LEK-informed modeling could help provide the community members with a stronger "voice" in natural resource governance.

In recent years, incorporating wildlife resource users' knowledge and perspectives into management decisions are increasingly being promoted globally (Danielsen et al., In review). Likewise, local stakeholders have increasingly been involved in modeling efforts undertaken by scientists, particularly in data provision (Bélisle, Asselin, LeBlanc, & Gauthier, 2018). The novelty here is the translation of a technical model into a tool that can be easily accessed and used by non-professionals. While this is an advantage to facilitate community participation, it can also be a disadvantage if the tool is improperly used—for example, by running the model if assumptions are not met. Moreover, with a simple demographic model, there is a risk of sacrificing accuracy of assessments for accessibility.

Our study describes the process of combining local and scientific knowledge into a population model and the local uptake of this model for one location and for one species. Globally, as a species, muskoxen are not threatened, but nonetheless, as is the case elsewhere in the species' range, the Ivittuut sub-population is essential to the local Arctic human community. The team for this project consisted of representatives of the community, government resource managers, and natural and social scientists. As a result, our study contributes to understanding whether a collaborative community-government approach to ecological modeling can help small rural communities in the Arctic develop economically and survive, within environmentally sustainable limits.

In this paper, we address one issue related to how a collaborative community-government approach can generate evidence for management decisions about natural resource harvesting levels. We describe the establishment and application of a community-led harvest calculator. The specific questions we address are: (a) How was the community-led harvest calculator developed? (b) How was it used? and (3) What was the outcome?

2 | METHODS

2.1 | Study area

Our study was undertaken in the Ivittuut region in Greenland (ca. 61°N 48°W; Figure 1). Previously, endemic caribou (*Rangifer tarandus groenlandicus*) occupied Ivittuut, but extirpation occurred in the 1890s (Winge, 1905). In an effort to gain access to a harvestable large ungulate, the community was responsible for translocating 15 (10 females, 5 males) juvenile muskoxen to Ivittuut in 1987. These came from the established Kangerlussuaq sub-population (ca. 67°N 51°W). Ivittuut herd abundance increased, largely owing to 8 years of harvest prohibition and absence of large predators in southwest Greenland. By 1990, numbers had more than doubled. In 1995, locals observed 150 muskoxen and hunting began.

Harvest was both subsistence and guided trophy and mostly by community members from Arsuk. Although ad hoc prior to 1998, thereafter annual counts were undertaken by community members from Arsuk but no information was compiled on the age and gender composition of the herd. Until 2010, the Ivittuut Municipality used the community members' counts to set annual muskox harvest quotas independently of, but in discussion with, the Greenland central government. Prior to 2015, we have no information on the herd size, the quotas set, the criteria used for setting them, and whether annual quota levels were reached. However, during 1995–2015, the annual harvests were reportedly a "small" proportion of the population based on the yearly counts.

By 2008, guided trophy hunting was well developed and providing an important economic contribution to the community. Guided muskox trophy hunting tours to Ivittuut cost ca. USD 6,000 per person, which includes hunting guide, lodging, local transport from the village of Arsuk, and one trophy bull (Feldmann, 2019). Given 73–84 trophy bulls are harvested annually (2015–2017; see *Supporting Information* Appendix S1 Table S1), this activity is of great economic importance for the small community of Arsuk. Subsistence hunting of the herd is also important for the Arsuk community.

In 2010, Greenland merged municipalities. This amalgamated Ivittuut into the larger Sermersooq Municipality, with control of harvest regulation transferred to Sermersooq and the central Greenland government. Conflict arose immediately between local community harvest of muskoxen (both guided trophy and subsistence harvest) and harvest by Greenlandic hunters living far outside the Ivittuut region (subsistence that often led to the killing of adult bulls). Arsuk community members became concerned about: (a) the sustainability of their commercially valuable guided trophy hunt; (b) the impact of "outside" hunters; and (c) what might be the optimal trade-off between guided trophy and subsistence harvest for their community. Representatives of Arsuk community therefore asked the Ministry of Fisheries, Hunting and Agriculture for assistance. In response, we initiated this project to develop a muskox harvest

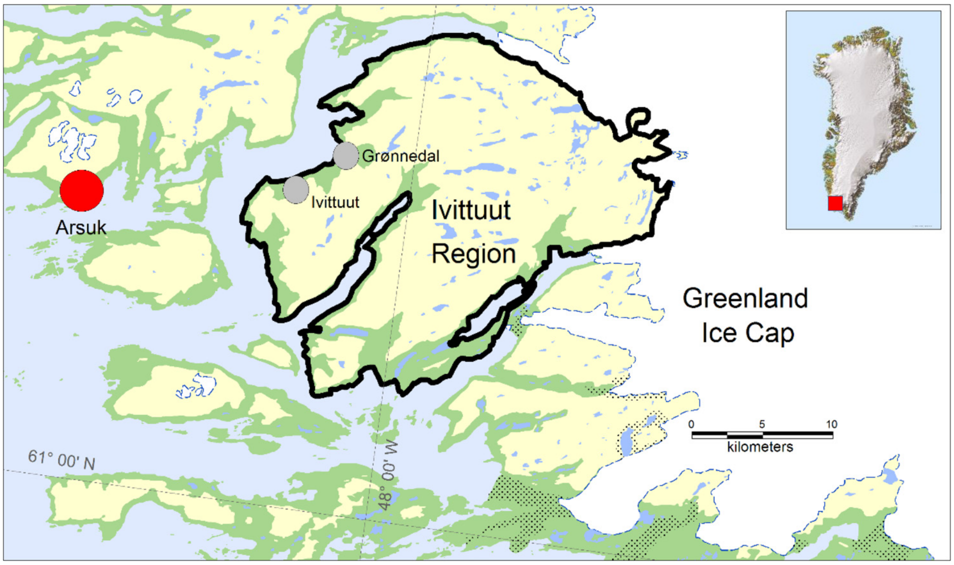

FIGURE 1 Ivittuut study area, ~430 km^2, and Arsuk community (population 67) in southwest Greenland. Grey circles are abandoned towns, Ivittuut and Grønnedal

calculator aimed at enabling the local community themselves to use their own annual count data to inform setting harvest quotas for the Ivittuut muskox herd.

2.2 | Method for developing the community-led harvest calculator

The community-led harvest calculator was developed over a three-year period, from 2015 to 2017, alongside the capacity building of government staff and community members in census of muskoxen and in local documentation and management of living resources. Our team comprised three professionals in wildlife management and administration from the Government of Greenland, a wildlife biologist, a rural sociologist, and a systems ecologist.

For the local documentation and management of muskoxen and other living resources, we followed an approach developed by the Government's Piniakkanik Sumiiffinni Nalunaarsuineq (PISUNA) programme (https://eloka-arctic.org/pisuna-net/; theoretical framework in Danielsen et al., 2014). In brief, a Natural Resource Council was established in Arsuk, comprising nine local hunters and fishermen and others with an interest in the environment. The council decided which species and environmental conditions should be observed in the Ivittuut region. The members compiled data on these attributes during hunting and fishing trips. Every 3 to 6 months, the data were summarized, discussed, and analyzed. Possible management interventions were discussed. The proposed management decisions and the supporting observations were forwarded to the government.

Four visits were made by the government staff, the biologist, and the sociologist to Arsuk to assist and support the community members and to establish the harvest calculator (June 4–12, 2015; June 23–July 6, 2016; June 8–15, 2017; November 8, 2017 [Table 1]). During the last two visits, the systems ecologist also participated.

2.3 | Method for the community members' census of muskoxen

The community members undertook post-calving field surveys of the Ivittuut muskox herd with the use of a simple census protocol (Cuyler, 2015). The surveys were minimum counts, comprising actual number muskoxen observed, with no correction for undetected animals. Field survey data prior to 2015 could not be used for our projections as it did not include any breakdown of sex and age. In brief, muskoxen were located by sailing open outboard boats along the coastline and by hiking up into principal valleys. Using Leica telescope or binoculars (32× and 10× magnification, respectively), muskox groups were examined for total number. When possible, sex and age cohort composition was recorded, and included calves born that spring, juvenile cows (aged 1–2 years), adult cows (≥3 years), juvenile bulls (aged 1–4 years), and adult trophy bulls (age ≥ 5 years). Tiny body size identified calves. Horn size/shape and body size determined sex and age of older animals (Alaska Dept. of Fish & Game, 2010; Henrichsen & Grue, 1980; Olesen & Thing, 1989). To avoid double counting, once a valley or coast was counted, it was considered "finished"; given the stationary nature of muskoxen, counting the same animal(s) twice is unlikely.

The annual 2015–2017 community censuses of the Ivittuut muskox herd were undertaken in June and July. Since the 1990s and also in 2015–2017 period, all

TABLE 1 Chronology of events for the collaboration between community members and external stakeholders on the management of the muskox herd in the Ivittuut region, Greenland 2015–2017, including the development and use of the community-led harvest calculator (n/a, not available)

Year	Day	Event	Outcome	Documentation
2015	June 4–10	Community members census the muskox herd, and they are trained in the minimum count census technique	The Ivittuut muskoxen stock censused. Two community members trained	Technical report
	June 11	Village meeting in Arsuk facilitated by staff of the Ministry of Fisheries, hunting and agriculture (3 h)	Discussed and obtained feedback on the overall aims and plans. Presented the idea of establishing a natural resource Council in Arsuk. Invited volunteer to engage	Minutes
	June 12	Natural resource council meeting facilitated by staff of the Ministry of Fisheries, hunting and agriculture (2 h 30 m)	Jointly agreed on the work of Arsuk natural resource council. Nine volunteers trained. Agreed on attributes to document in the Ivittuut region. Appointed local coordinator for the council	Minutes
	December	Natural resource council meeting facilitated by the local coordinator	Documented and discussed trends in muskox and environmental conditions in the Ivittuut region and possible management actions	Minutes
2016	March 15	Natural resource council meeting facilitated by the local coordinator	As above	Minutes
	June 23 to July 2	Community members census the muskox herd, and they are trained in the minimum count census technique	The Ivittuut muskoxen stock censused. Two community members trained	Technical report
	July 6	Natural resource council meeting facilitated by staff of the Ministry of Fisheries, hunting and agriculture (4 hr)	Discussed the plans and progress of the work of Arsuk natural resource council. Discussed trends in muskox and environmental conditions in the Ivittuut region, and possible management actions	n/a
2017	March 15	Natural resource council meeting facilitated by the local coordinator	Documented and discussed trends in muskox and environmental conditions and possible management actions	Minutes
	June 8–13	Community members census the muskox herd, and they are trained in the minimum count census technique	The Ivittuut muskoxen stock censused. Two community members trained	Technical report
	June 15	Natural resource council meeting facilitated by staff of the Ministry of Fisheries, hunting and agriculture (1 hr 35 min)	Presented and discussed the idea of establishing a user-friendly calculator for the Ivittuut muskox herd. Discussed the aims of the calculator, language, assumptions, key parameters, birth rate, natural mortality rate, and proportion missed animals on the community members' census	Minutes
	November 8	Natural resource council meeting facilitated by staff of the Ministry of Fisheries, hunting and agriculture	Presented and discussed a preliminary version of the calculator. Obtained feed-back and jointly revised it. Trained community members in its use. Scenarios developed by the community members. Proposal for 2018-quota prepared, discussed, and agreed upon	n/a

censusing was led by the government's hunting officer, an Arsuk local. A wildlife biologist supported the 2015–2017 community members' censusing of the muskox herd, and trained community members in muskox sex and age identification and census protocol. In 2015, 2016, and 2017, the community members observed 1,261, 917, and 812 muskoxen, respectively (for details on age and sex structure, see *Supporting Information* Appendix S1 Tables S2A, B, C).

3 | RESULTS

3.1 | Development of the community-led harvest calculator

The development of the harvest calculator involved (a) meetings with Arsuk Village Committee (*bygderåd*), (b) community censuses of the Ivittuut muskox herd, (c) a village meeting, and (d) establishment and facilitation of a PISUNA Natural Resource Council of hunters and fishermen in Arsuk (Table 1). All the meetings were undertaken in Greenlandic, Danish, or English, with translation to Greenlandic. We contacted the Arsuk Village Committee through the Sermersooq Municipality to introduce the initiative to the Committee and obtain their advice. We explained that the objective was to test local government initiatives on documentation and management of the local sub-population of muskoxen so as to contribute to better management of this and other herds in Greenland.

A village meeting was held, June 11, 2015 (Table 1), in Arsuk to discuss and agree on the objectives and plans of the initiative, and to obtain input from the community members. The meeting was facilitated by staff of the Ministry of Fisheries, Hunting and Agriculture. Two presentations were given: one regarding the background, purpose, content and opportunities for participation, and the other regarding the results of the minimum count of muskoxen. The participants were encouraged to voluntarily engage in documenting and managing the herd. It was explained that a Natural Resource Council would be created to monitor the herd, and that the members of the Council would meet regularly to analyze and agree on trends in the herd and to make proposals, as required, to the government regarding management. It was also explained that such local participation should ensure that condition and management of the herd were both well documented, well adapted to local conditions and equitable. Finally, participants were told that in Greenland there is a limited understanding of muskox herds, and, since government agencies will only to a very limited extent be responsible for future herd assessments, it would be best to transfer greater responsibility for quota setting to the local users of the herds. It was made clear that Arsuk was chosen for this case study because there is already some experience of local involvement in the management of the Ivittuut muskox herd.

As a result, there was substantial local interest in being involved in the management decisions for the muskox herd. There were numerous ideas for action put forward by community members with respect to strengthening local management of the herd. The village meeting concluded with interested participants being encouraged to join the Natural Resource Council, if they had interest in it and experience with muskoxen and other natural resources in the Ivittuut region. Nine participants signed up, including muskox hunters, trophy-hunting outfitters, and others with a stake in the muskoxen and resources in the Ivittuut region.

At the first meeting of the Natural Resource Council, June 12, 2015 (Table 1), the community members each first confirmed their interest in participating in the Council. It was agreed that the Council would try to meet every three months to discuss the trends in the conditions affecting the muskox herd. The meeting concluded with the appointment of a local volunteer coordinator tasked with convening Council meetings, preparing minutes of meetings, and liaising with the authorities. From 2015 to 2017, Arsuk Natural Resource Council met twice each year.

Several subsequent meetings elaborated on the role of the Natural Resource Council, to monitor the herd and the conditions potentially affecting the herd, to undertake a census of the herd every year, and to meet regularly in order to discuss trends and review management alternatives. The Natural Resource Council agreed to monitor the following attributes relevant to the management of the Ivittuut muskox herd:

- Muskox population changes from year to year (number, sex, and age structure) through minimum counts
- Diseases in the muskox herd
- The quality of the animals slaughtered
- Changes in the vegetation of selected pastures for early detection of overgrazing
- Poaching of muskoxen
- The use of licenses for hunting muskoxen
- Distribution of the muskox herd within the Ivittuut region
- Activities around the southern border of importance to the muskox herd
- Procurement of meat to the factory in Arsuk in relation to the factory's operation.

A format for documenting observations was discussed and agreed upon. The Council's July 6, 2016 meeting

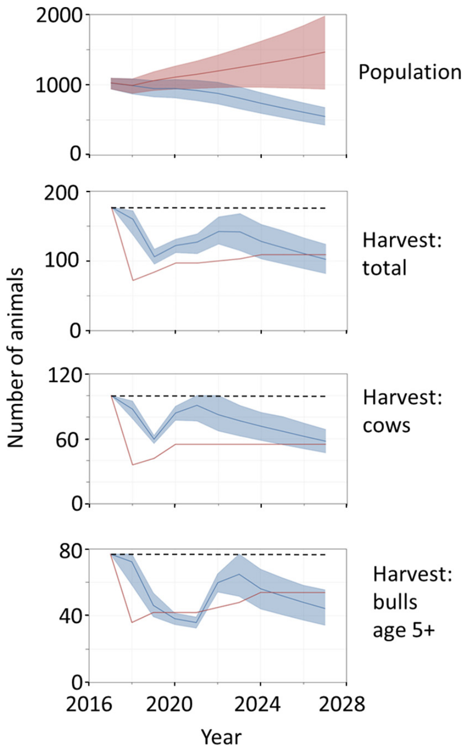

FIGURE 2 Results from Inuit community members' use of a wildlife harvest calculator informed by their own observations in the field. Community members' projections of the future population and harvest opportunities for the Ivittuut muskoxen herd, Greenland, during 2018–2027, including total population, total harvest, harvest of cows (for meat for subsistence), and harvest of bulls age ≥ 5 years (for guided trophy hunting). Blue lines indicate the mean projection assuming harvest recorded in 2017 (shown as dashed line) continues as the quota each year into the future ("business-as-usual"). Red lines show the mean projection under the revised harvest quota scenario (starting in 2018) developed by the community members. Colored zones indicate the corresponding 95% Monte Carlo confidence intervals for model projections over 1,000 Monte Carlo realizations; red lines without colored zones have 95% confidence intervals that overlap with the mean

(Table 1) also presented a wide range of management ideas, such as local issuing of licenses, and potential forced migration of parts of the muskox herd to adjacent larger tundra areas. It was made clear that these proposals would be something that the Natural Resource Council could expand upon in the future. Communication channels in connection with proposals for management were also discussed and agreed upon, and the Council expressed a desire to communicate directly with the central government to reduce delays on the part of the municipal administration.

In June 2017, the government resource managers introduced the idea of establishing a user-friendly demographic model to project the future consequences of management decisions on the muskox herd (Table 1). After the idea of developing a model was explained and discussed in the Council, the members agreed that a model could be a relevant mechanism for developing quotas. Annual quota setting is the key management tool for regulating muskox sub-populations in Greenland. They also agreed on the objective of the model. The model should enable them to use their own annual count data to inform setting harvest quotas, by sex and age, for the Ivittuut muskox herd, as independently of external experts as possible.

For establishing the population model, we used an existing software tool, DG-Sim (ApexRMS, 2018; Frid, Hegel, Russell, & Daniel, 2014), and met in Arsuk November 8, 2017 (Table 1). Together with Arsuk Natural Resource Council we adapted this software to project possible future fates of the Ivittuut muskox sub-population. DG-Sim is a general population-modeling framework that uses a stochastic, stage-structured matrix approach to project abundance over time (Caswell, 2001). Key features of the DG-Sim software for this study included: (a) a user-friendly interface, (b) multi-language support, and (c) an underlying stochastic framework for projections. The user-friendly nature of DG-Sim permitted the Arsuk Natural Resource Council to interactively undertake "what-if" analyses of model projections. The multi-language support made modeling equally accessible to scientists, government managers and community members; software ran simultaneously in three languages: Greenlandic, Danish, and English. Finally, the stochastic nature of DG-Sim allowed model projections to incorporate uncertainty in model inputs, such as initial population size and demographic rates, including uncertainty in the estimates provided by community members. Thus, the model was able to convey to the local community members the risk that was associated with different harvest scenarios. All of these features were thought to be important in allowing us to build trust in the model with community members, as they allowed us to work with the community interactively—both in workshop settings and one-on-one—to explain, parameterize, and run the model.

3.2 | The use of the community-led harvest calculator

We explored the effects of alternative future harvest quotas by using a series of future "quota setting" scenarios, from 2017 to 2027. Model inputs included estimates of birth rates, natural mortality rates, target harvest levels (i.e., harvest quotas), and initial sub-population size (by sex/age cohorts). The model was parameterized

TABLE 2 Examples of knowledge contributions by community members and external stakeholders to the modeling process for the community-led harvest calculator

	Knowledge contributions and perspectives	
Steps of the modeling process	**Community members**	**Government resource managers, and natural and social scientists**
Setting objectives	The community members would like the model to enable them to use their own count data to inform muskox quota-setting	Government staff raised funds and gathered expertise for community-led resource management, model establishment, and training
Developing the conceptual model	The community members described the key attributes of importance to the development of the Ivittuut muskox herd to ensure a sustained supply of cows for meat and bulls for trophy harvest	Experiences from elsewhere in Greenland and internationally were incorporated into the model
Data provision	The community members carried out annual post-calving counts under supervision of a biologist, and the data were used in the model	The census protocol was developed by the biologist, who also trained the community in data provision, including muskox age and sex determination
Analysis and parameterization	The community members parameterized the model with their estimates of undetected animals and life expectancy; their knowledge of the environmental and socio-cultural conditions of the Ivittuut area enabled scenario interpretation	The systems ecologist converted the community members' estimates of life expectancy to a corresponding annual mortality rate
Use of the results for quota-setting	The community members used the model to predict future muskox abundance and proposed harvest quotas to the government	The government resource managers approved the community members' proposal for quotas with its supporting, calculator-based scenarios

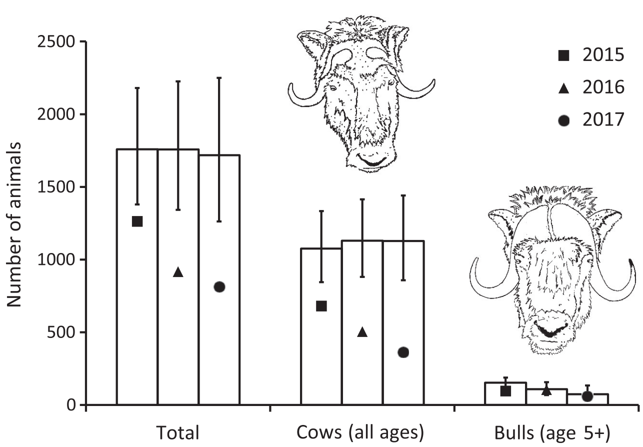

FIGURE 3 Community minimum counts (symbols) and corresponding population projections for the Ivittuut muskoxen herd, Greenland, for the years 2015, 2016, and 2017. Columns show the mean model projection for each year, including error bars indicating the 95% Monte Carlo confidence intervals for each model projection over 1,000 Monte Carlo realizations

with the community members' own estimates of undetected animals and life expectancy. In estimating life expectancy, we asked community members to estimate a range (i.e., minimum and maximum) for the average age at which an animal of each sex dies of natural causes. The range for each sex's life expectancy was then converted to a corresponding annual mortality rate using the formula $m = 1 - 0.5^{1/a}$, where a is life expectancy (in years) and m is the corresponding annual mortality rate. Uncertainty in this mortality rate was then represented in the population model by sampling, by sex, from a uniform distribution bounded by the range of the estimated mortality rates. Further details on population model parameterization are available in *Supporting Information* Appendix S2. The community members used their count data and modeled different harvest scenarios. Community members estimated that mean population size of the herd was 25–30% greater than the survey minimum count, and that life expectancy of bulls and cows were 11 (range: 9–13) and 18 (range: 15–20) years, respectively.

Community members themselves also projected the consequences of several possible future quotas. We describe two relevant projections in detail (Figure 2). The knowledge of the community members, and external stakeholders were involved in all key steps of the modeling process (Table 2). This included the setting of objectives, developing the conceptual model, data provision, analysis, and parameterization, and use of the results for informing quota decision-making. The first quota-setting scenario, shown in blue in Figure 2, is "business-as-usual", in which the quota for all future years (i.e., from 2018 onward) is set to be the same (number, sex, and age) as the reported 2017 harvest. The community realized that the 2017 harvest is not likely to be sustainable into the future, and that future subsistence harvest should only consider cows in order to maximize the availability of bulls for the lucrative trophy harvest. Beyond 2017, the current quota is unachievable. There is an eventual steady decline projected in harvest of both cows and trophy bulls and an overall decline in the sub-population. Here, there is also considerable uncertainty regarding the level of harvest, as indicated by the width of the confidence intervals around mean projections (the blue zones in Figure 2).

The second quota-setting scenario, shown in red in Figure 2, is one in which harvest of both cows and bulls is reduced considerably in 2018 (i.e., quota of 177 in 2017 curtailed to 76 in 2018), and then gradually increased again from 2018 to 2024. This resulted in a projected steady increase in overall sub-population, a sustained supply of meat from cows, and by 2027, an overall harvest of trophy bulls exceeding that from "business-as-usual." Furthermore, and of utmost importance to the community, there is a high degree of certainty that the projected trophy bull harvest will be achieved. As shown in Figure 2, the 95% Monte Carlo confidence intervals (over 1,000 Monte Carlo realizations) overlap with the mean projections for all future timesteps, indicating that, despite the uncertainty in model inputs, the proposed quota is very likely to be sustainable.

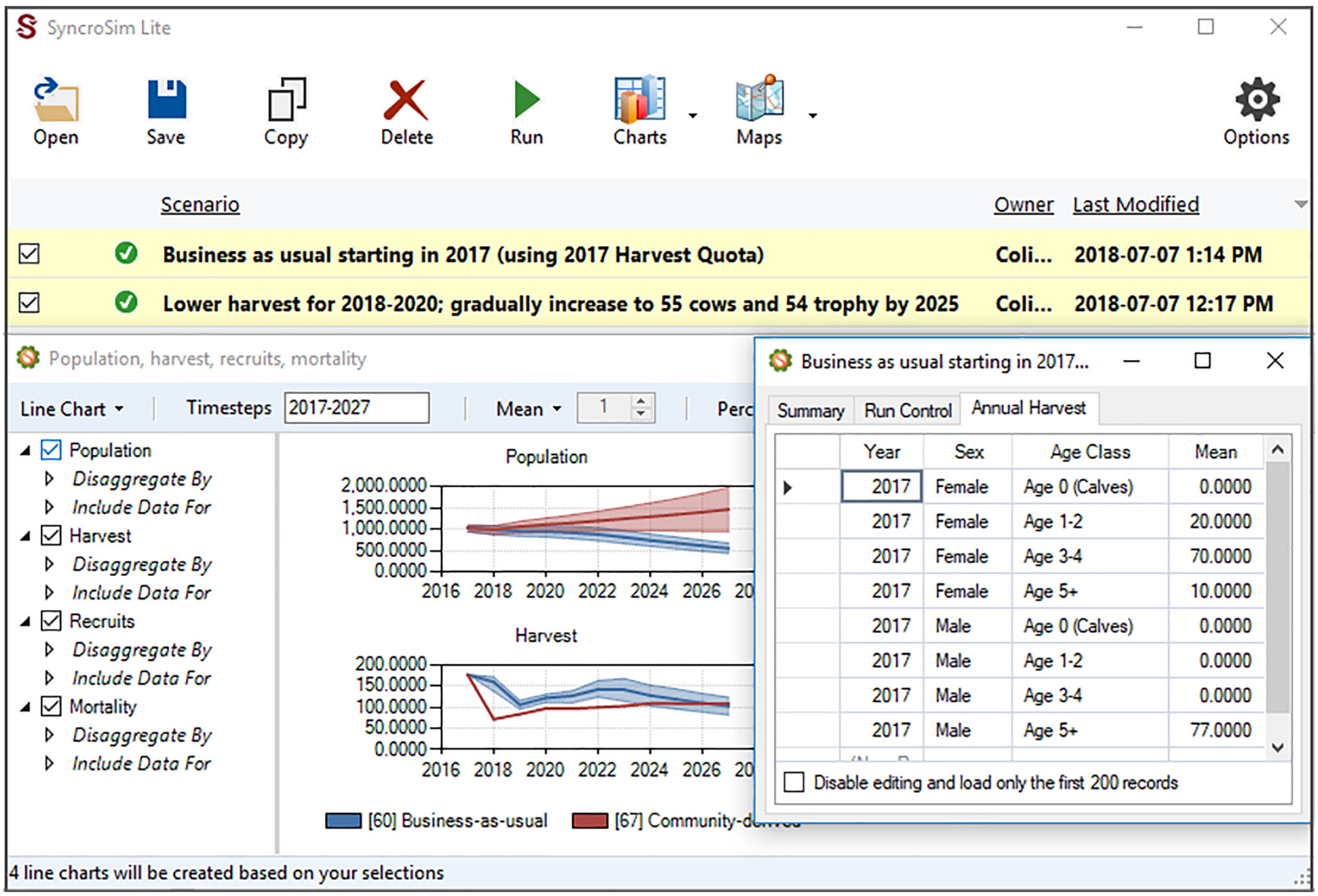

FIGURE 4 User interface of the DG-Sim population model, as configured in English for the Ivittuut muskoxen herd. Key features of the DG-Sim user interface included its simple display of tables and graphs, and its ability to switch between multiple languages; for this project, we configured DG-Sim to run in English, Danish, and Greenlandic

3.3 | The outcome of using the community-led harvest calculator

The model results for the different scenarios were discussed and compared with the management objectives for the muskox herd. The aim was to obtain a sustained and relatively stable supply of harvestable trophy bulls and animals for meat supply. The community members decided on the scenario that best fitted this objective. They decided to use that scenario in their request to the government for a muskox harvest quota in the Ivittuut region of 76 animals for 2018 (as compared with the 2017 quota of 177 animals). We found that this led to immediate approval of the quota by government wildlife management authorities.

To assess whether the projections and the survey results corresponded, we compared muskox population projections against community members' field survey results from 2015 to 2017. We used the community members' minimum counts in 2015 and projected muskox sub-population size for 2016 and 2017 with a model parameterized with scientific opinions of undetected animals and life expectancy. We assumed the scientific opinions that mean population size was from 40 to 100% greater than the minimum count, and that estimated life expectancy (in absence of harvest) of bulls and cows was 6–8 years and 8–11 years, respectively. We found that when the community members' survey results varied considerably from year to year, the forward model projections showed only a slight decline in total sub-population over the 2-year period, although uncertainty in the projections increased over time (Figure 3). However, for trophy bulls (i.e., age more than 5 years), both the model projection and the community members' survey found a decline in numbers from 2015 to 2017.

TABLE 3 Preliminary protocol to help decide where community-led harvest calculators are appropriate (adapted from Danielsen et al., 2011)

Who	Positive attributes
The local community	Experience in community management of natural resources
	Evidence of trusted community organization and leadership
	Residents show interest in sustainable wildlife management
	Residents utilize wildlife resources
	Clear rights over wildlife resources are present in practice
The government	Government policy is in place for shared management of wildlife resources with communities
	Procedures and rules are clear, for example, on benefit distribution to directly involved communities, and verification of community wildlife census results
	Government authority and advisory scientists will accept data generated by community members at the local level
Intermediate organization	Presence of suitable and interested intermediate organization with experience of working with communities, within reasonable distance of the wildlife resources concerned
The wildlife species and the area	The wildlife species population should be quantifiable in absolute numbers, tonnes, or another unit
	Discernable wildlife sub-population, clearly separated from other sub-populations
	Above a minimum threshold on wildlife sub-population size needed to break-even on transaction costs of censusing and modeling
	Evidence that community management will ensure sustainable use of the species

4 | DISCUSSION

The collaboratively developed wildlife harvest calculator was adopted immediately by both the community members and the government in support of decisions regarding harvest quotas for Greenland's Ivittuut muskox sub-population. The population model projections corresponded with the decline in trophy bulls observed by the community members. The community-led harvest calculator made it possible for the community members in Arsuk themselves, for the first time, to identify and discuss locally desirable muskox harvest scenarios over multiple years.

Fundamental to the strong local uptake of the harvest calculator was that the population model was easy to parameterize and that it operated in the local language. The user-friendly nature of the DG-Sim software was critical to the success of the calculator. For community members to trust the model's projections, we found that they needed to first agree with and accept the modeling approach. This required that the model's assumptions, data and projections all be presented in a format that the community members could understand. The ability of DG-Sim to run in Greenlandic was important in this regard, as was the software's built-in capabilities for displaying all of the model inputs and exploring alternative "what-if" scenarios interactively with community members (Figure 4).

The community members used assumptions about vital rates of the muskox herd based on their own knowledge and understanding, developed since 1987 when muskoxen were introduced to the area. The meetings in the Natural Resource Council were a careful process involving time, commitment, and underlying trust. The community members were in control of this process—agreeing what was right and wrong and ensuring that information on birth rates, natural mortality and initial herd size was discussed and agreed upon for use in the projections. This was key to gaining community acceptance of the harvest calculator and ownership of the resulting projections.

The difference between the counts observed by community members and the projections of the model for 2015–2017 could be due to one of several possible factors, including incorrect model estimates for demographic parameters (i.e., birth rates and natural mortality rates), underestimate of the modeled versus actual harvest, and missed animals in the community members' censuses of the muskox herd. The 95% Monte Carlo confidence intervals shown for the model projections in Figure 3 are intended to account for uncertainty regarding scientists' estimates for the first two of these factors (demographic rates and harvest), along with uncertainty regarding the 2015 population estimates. Because the community counts lie outside of these confidence intervals for all years, it is most likely that the difference between the model projections and community counts is due to missed animals in the community counts. Furthermore, it is possible that the decline in community counts from 2015 to 2017 is due in part to an increase in the proportion of animals missed.

The certainty of a sustainable trophy bull harvest was of primary importance to the community members. Since estimates of sub-population size by the community members were conservative (i.e., lower than scientists' estimates), this led to cautious quota setting. This enabled the community members to plan the number of guided trophy hunts 1–2 years in advance, and permitted them a measure of security regarding future incomes, while still obtaining meat from cows for food. Because confidence intervals were provided for projections of both sub-population levels and harvest, the community was able to assess the risk of not achieving their target harvest quota for both trophy bulls and cows. As shown in Figure 2, continuing the 2017 harvest quota into the future leads to considerable uncertainty regarding how many animals can be harvested in any 1 year, both for cows and for trophy bulls. In contrast, the new harvest quota selected by the community members is projected to be achievable across all 1,000 Monte Carlo simulations—in other words, a very conservative quota, given the uncertainties acknowledged in the model, yet a quota upon which the community members could plan for the future with confidence.

In this study, we were not able to assess the accuracy of our model projections. A detailed assessment of the accuracy of the model would require additional data on sub-population size and demographic rates, which is unlikely to ever be collected for a herd of this size and in such a remote location. Rather, the data shown in this study is likely as much as this community will ever have to work with in making projections.

Like most simple stage-based matrix population models, a limitation of the current model is that it does not account directly for several factors that could influence future population levels in the herd, including the effects of insects, pathogens, and changes in habitat (e.g., through overgrazing or climate change). However, we believe that without the data to support it, adding additional complexity to the model would probably lead to a reduction in model parsimony, with a concomitant reduction in explanatory power and thus predictive capability (Dietze, 2017). It is for this reason that we chose to develop our model using the stochastic framework of DG-Sim, which allowed us: (a) to keep the model parameterization simple, so that we could in fact parameterize the model effectively using only limited data, and (b) to explicitly incorporate uncertainty into our estimates of all model parameters and, in turn, using a Monte Carlo simulation approach, reflect this uncertainty in the model projections. As shown by the confidence intervals in Figure 2, there is considerable uncertainty regarding the population projections for both scenarios considered by the community. This is to be expected, given the paucity of data available to make projections. Even considering all this uncertainty, however, the "business as usual" scenario shows a consistent decline in the population across all Monte Carlo simulations, while the "revised harvest quota" does not. As a result, for community members it is clear that one quota alternative is more likely to be sustainable than the other. Generating projections in a timely manner, and in a way that explicitly acknowledges the combined uncertainties of both scientists and the community, was a key element in building trust with community members in the modeling process, and in turn leading to acceptance of the model's projections.

A central uncertainty in the model projections is the initial sub-population size and composition. As outlined previously, the 3 years of community surveys are only minimum counts, and were undertaken in a way that makes it difficult to assess the proportion of animals counted versus missed. The community's solution to this challenge, however, was a very reasonable one: to act conservatively and assume that very few animals were missed in the counts. This resulted in the model projecting lower sub-population levels than would have resulted from scientists' estimates, and in turn led to the community accepting a lower harvest quota than might otherwise have been projected by scientists alone.

Another limitation of the population model is that, like many population models, it does not account for possible effects of skewed sex-ratios on recruitment (Schmidt & Gorn, 2013). Note, however, that, for the harvest quota selected by the community in this initiative, the model's mean projection for the adult (i.e., mature) sex ratio rises from 50 to 70 bulls/100 cows over the period from 2017 to 2027, suggesting that this ratio will become less skewed over time as a result of the proposed reduction in trophy bull harvest.

While we did not evaluate how accurate the harvest calculator is at prediction, we have shown what modeling can be undertaken in practice by community members in the "real" world, and we have demonstrated the benefits that can be obtained from establishing a community-led harvest calculator in community-managed areas. Allowing community members to run the model with their own estimates of uncertainty for model inputs—albeit informed by scientist's uncertainty estimates—was a key element of building trust and acceptance within the community in the model's projections. Both the government and the community were aware before our modeling began that overharvesting was likely occurring for the herd, particularly for bulls. This likely helped prime both parties for quota reductions. What was uncertain, however, was by how much harvest should be reduced, and what the age/sex structure of the harvest should be in order to meet the dual objectives of subsistence and trophy harvest. We believe that the simplicity of the model helped to gain acceptance, as the parties involved could trace through the consequences of various assumptions, including both theirs and those of the scientists, on the eventual projections. True engagement with the community was also critical—in particular, explaining the details of the model calculations, and allowing community members to revise the scientists' parameter estimates.

Many communities in the Arctic and elsewhere are seeking a greater role in decision-making and harvest regulation for resources that the communities are dependent upon (Amos & Turner, 2018; Bélanger, Guile, & Meinert, 2018; Leon, 2018; Netser & Greene, 2018; van der Wielen & Modeste, 2018). The community-led harvest calculator could play an important role in this regard. LEK-based population models are likely to be particularly valuable in sustainable use contexts when local stakeholders are utilizing a wildlife resource of high economic value, and when they simultaneously, have a major stake in the management of this resource. A community-led harvest calculator is therefore relevant and likely applicable in many communities across the world. We have developed a preliminary protocol to help decide whether the key conditions are in place for applying and sustaining community-led harvest calculators (Table 3). The protocol is intended for the preliminary planning of community-led harvest calculators and further work would be needed at the local level to verify and substantiate these variables on the ground. Furthermore, the harvest calculator will only be truly successful if the local community continues applying this tool systematically in the future to support their management decisions.

In conclusion, wildlife population modeling using LEK at all steps equipped local stakeholders in Greenland with the capacity to explore the results of "what-if" harvest scenarios on future population size and composition for their local muskox sub-population. The results directly influenced subsequent harvest management decisions. Our findings suggest that further use of LEK in wildlife population modeling in community-managed areas could contribute to meeting the Aichi Target 18 goal for the Convention on Biological Diversity. Moreover, our findings demonstrate how collaborative community member and external stakeholder evidence can be compiled and used for evidence-based decision-making in community-managed areas.

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AUTHOR CONTRIBUTIONS

C.C., a biologist, participated in annual Arsuk meetings, trained census observers, supported community-led censuses, and facilitated use of the community-led harvest calculator.

C.J.D., a systems ecologist, created community-led harvest calculator and, in Arsuk, supported locals familiarity and use of that calculator.

M.E., a sociologist, participated in annual Arsuk meetings and facilitated use of the community-led harvest calculator.

N.L., Government staff, aided revision of manuscript, and facilitated use of the community-led harvest calculator and communication of results to the Greenland government.

N.M.-L., Government staff, participated in annual Arsuk meetings and facilitated use of the community-led harvest calculator.

P.N.H., Government staff, hunting officer, and Arsuk local, who since the 1990s has been responsible for and led all censuses of Ivittuut muskoxen, participated in annual Arsuk meetings, and facilitated the Arsuk Natural Resource Council.

D.D., a project staff, reviewed initial literature and aided revision of manuscript.

F.D., a project leader responsible for obtaining funding, and contributed to the design of the research.

ETHICS STATEMENT

All muskox censuses were in accordance with ethical standards of the Greenland government. Muskoxen were observed using 10× binoculars and 32× telescopes, and 500 m minimum distance between motorized vehicle and animal.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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SUPPORTING INFORMATION

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

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