CAPARDUS - Capacity-building in Arctic standardization development

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Deliverable 2.2

Technical guidelines for the integration of Local and Indigenous Knowledge in Bayesian Belief Network models with halibut fisheries in West Greenland as an example

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EXECUTIVE SUMMARY

Climate change is occurring faster in the Arctic than in any other region, with tremendous consequences for Arctic biodiversity and the indigenous peoples and local communities that depend on it. Climate and biodiversity change can undermine established production patterns of hunting, fishing, gathering, and herding by Arctic communities, negatively influencing their welfare and wellbeing. The ecological and societal changes facing small-scale rural users and indigenous groups in the Arctic may surpass their resilience and adaptive capacity.

Future scenario analysis incorporate uncertainty arising from complex interactions between climate and biodiversity change and other sector activities are increasingly relevant for conservation and development planning in the Arctic to encompass the intertwined interactions between humans and their natural environment. Bayesian Belief Network (BBN) models offer an opportunity to explore such complex socio-ecological systems with limited data by incorporating scientific knowledge as well as Local and Indigenous Knowledge (LIK), making it possible to make predictions about the outcome of management interventions in future scenarios.

Here we provide a brief overview of the potential of BBN models as a flexible tool to combine scientific data and knowledge and LIK to reflect complex socio-ecological systems and assess the outcome of potential policy interventions meant to address natural resource management problems in Greenland. Hence, this deliverable is written by scientists for scientists and natural resource managers. To illustrate the potential of BBN models, we present a **preliminary** model for the coastal halibut fishery in West Greenland implemented in the *surBayes* software. The model should be seen as a conceptual framework and an illustrative example only because we could not engage in the required co-development with experts and relevant communities due

to the Corona pandemic. We provide a step-by-step introduction to the *surBayes* software. We then use available experience in the literature, mainly on community-based monitoring in Greenland and elsewhere, to reflect on guiding principles and ethical considerations as well as how to promote the inclusion of LIK in BBN models for natural resource management in Greenland.

There is growing recognition of the need to engage with and utilize LIK in a more comprehensive and meaningful way to improve our understanding of social-ecological interdependencies, promote innovation, and contribute to the identification of desirable pathways for the future with increased legitimacy and trust in decision-making. Participatory modelling approaches, including co-developing BBN models, can draw on the subjectivity that is inherent in sustainable use contexts when local peoples are utilizing wildlife or fish resources of high economic value and when they simultaneously have a major stake in the management of this resource. Still challenges in the use of LIK exist regarding language barriers and differing worldviews that can hinder communication, mutual understanding and reaching consensus. We briefly review the relevant literature and provide recommendations for a set of standards for inclusion of LIK in BBN models.

The use of LIK may also have ethical implications. Efforts to integrate indigenous and science-based knowledge systems for co-management of wildlife have, in some cases, led to the de-contextualization and compartmentalization of indigenous knowledge through its translation (and distortion) into forms that can be incorporated into existing management bureaucracies and acted upon by scientists and resource managers. How to ethically appropriately connect information generated by different knowledge systems to inform natural resource management remains a key challenge. Here, we synthesize guidelines for appropriate ethical conduct in relation to obtaining LIK for BBN models. Doing so we combine relevant aspects of ethical guidelines developed by, and thereby also vetted by ethnic groups themselves.

Experience evaluating how to best promote the use of LIK informed BBN models by government administrations for natural resource management is scant, especially in an Arctic context. However, valuable insights may be gained from studies describing experience with community-based monitoring and a community-based harvest calculator in Greenland as well as a review of literature about connecting top-down and bottom-up approaches in environmental observing. We summarise insights from this literature to a set of recommendations and suggestions for future avenues of research into how to best encourage use of LIK informed BBN models in the administration of Greenland’s natural resources.

Finally, this updated version of the deliverable includes a description of the session in the Aasiaat workshop (Deliverable 2.3) where BBN models were introduced to a range of partners in Greenland’s natural resource management although this took place after the submission of the initial version of this deliverable.

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1. Introduction

Climate change is occurring faster in the Arctic than in any other region (IPCC, 2014), with tremendous consequences for Arctic biodiversity and the people that depend on it (AMAP, 2011; CAFF, 2013; AHDR, 2014). The ocean is the basis of Arctic communities' livelihoods but is warming rapidly with no recent historical precedent for the 21st century's minimum sea ice extent (Walsh et al., 2017).

Climate and biodiversity change can undermine established production patterns of hunting, fishing, gathering and herding by Arctic communities, negatively influencing their welfare and wellbeing (ECONOR, 2008). Changes furthermore occur in a context of far-ranging economic, cultural and political change (ECONOR, 2015), including other sector activities such as extractive industries including mining, forestry, commercial fisheries and infrastructure and housing development in the same areas.

The ecological and societal changes facing small-scale rural users and indigenous groups in the Arctic may surpass their resilience and adaptive capacity (ACIA, 2005; CAFF, 2013; AMAP, 2013; AHDR, 2014). Therefore, it needs urgent assessment to reduce adverse social and ecological outcomes (Arctic Council, 2016). Physical and economic forecasts and scenario assessments are required to assess climate and biodiversity change impacts on Arctic communities and explore adaptive management options under global policies and trends (NRC, 2014; ECONOR, 2015). Particularly social science research describing the systems that are part of ongoing changes is underrepresented and needed to inform decisions (NRC, 2014; Arctic Council, 2016).

Hence, future analysis is increasingly relevant for conservation and development planning in the Arctic to incorporate uncertainty arising from complex interactions between climate and biodiversity change and other sector activities. Successful adaptation to these changes depends on the interventions made now. However, management options are many and varied and will individually and combined have welfare and ecological effects that are difficult to predict in highly linked systems characterized by incomplete data and cascading effects.

However, in vast areas of the world, ecosystems are governed primarily by Indigenous Peoples and Local Communities (IPLC) (Garnett et al., 2018; Brondizio and Le Tourneau, 2016), whose knowledge systems and practices are as diverse as the locations and groups from which they emanate. IPLC's in situ knowledge and practices have the potential to make significant contributions to addressing contemporary sustainability challenges both locally and globally. Definitions and terminology are many and varied, but overall Local and Indigenous Knowledge (LIK) is generated and developed through close interactions with the environment grounded in lived experience, often through stewardship practices (Huntington 2000; Tengö et al., 2017, 2021; Turner et al. 2022). These can include selection and domestication of crops and animal breeds, hunting and harvesting, habitat management and restoration, but also cultural practices, observation, and experience (Tengö et al., 2021).

In 1985 the responsibility for hunting and fishing, including the legislative power was transferred to the Greenland Home Rule. As the Greenland Inuit, the indigenous peoples of Greenland, are the majority population in Greenland, the terminology for ‘user knowledge’ applied in the Legal Act on Hunting (2023) has inspired the terminology used.
§ 2 in the act states that the management of the act is considering – among other factors - ‘the rational and the optimal seasonal harvest in agreement with conventional biological advice and

accessible hunters' knowledge and user knowledge.' The official comments to the Legal Act on Hunting further defines 'knowledge' in the following statement: 'A sustainable use of the hunting resources can be ensured 'by involving the recommendations of biologists or by involving the Hunters' Council, knowledge of hunters, local knowledge and user knowledge.' (Legal Act on Hunting (2023).

The legal Act on Hunting thus both focuses on the local aspect of knowledge and on the knowledge holders, the hunters. As LIK also focuses on the local aspect of knowledge and the indigenous peoples as knowledge holders we have found it reasonable and relevant to apply the term Local and Indigenous Knowledge. Similarly as various groups and institutions are or should be partners in managing Greenland's natural resources we use the term "partners" rather than stakeholders in this deliverable (other CAPARDUS deliverables may use other terminology depending on the context and the considerations of the authors of these).

The scarcity of data and the complexity of the intertwined interactions between humans and their natural environment (i.e., social-ecological systems) remains a challenge, but Bayesian Belief Network (BBN) models offer an opportunity to explore such complex socio-ecological systems with limited data by incorporating both scientific knowledge and LIK, making it possible to make predictions about the outcome of management interventions in future scenarios.

Here we provide a brief overview of the potential of BBN models as a flexible tool to combine scientific data and knowledge and LIK to reflect complex socio-ecological systems and assess the outcome of potential policy interventions meant to address natural resource management problems in Greenland. Hence, this deliverable is written by scientists for scientists and natural resource managers. To illustrate the potential of BBN models, we present a preliminary model for the coastal halibut fishery in West Greenland implemented in the *surBayes* software. However, the model should be seen as a conceptual framework and an illustrative example only because we could not engage in the required co-development with experts and relevant communities due to the Corona pandemic. Hence, the model cannot be used for making actual predictions. Nevertheless, the model and the *surBayes* software platform was presented at the conference and research school held by the CAPARDUS project in Aasiaat, Greenland, in December 2022, where it formed the basis for participants to implement their own scenarios and evaluate the potential of BBN models for use in complex, data deficient natural resource problems by enabling use of LIK. Roel May (NINA), a partner in the CAPARDUS project, has developed the *surBayes* software to facilitate the implementation of BBN models. We provide a step-by-step introduction to this software.

We then use available experience in the literature, mainly on community-based monitoring in Greenland and elsewhere, to reflect on guiding principles and ethical considerations as well as how to promote the inclusion of LIK in BBN models for natural resource management in Greenland. Synthesizing guidelines for appropriate ethical conduct in relation to obtaining LIK for BBN models we combine relevant aspects of ethical guidelines developed by, and thereby also vetted by indigenous groups themselves.

This document will also constitute the technical guideline and handouts for the research school held by the CAPARDUS project in Assiaat, Greenland, in December 2022.

2. BBN model advantages

BBN models have several advantages. As mentioned, BBN's are well suited to model socio-ecological systems characterized by incomplete information about the relationships between components of the system due to their ability to integrate multiple issues, interactions and outcomes and investigate trade-offs, utilizing data and knowledge from different sources (Chen and Pallino, 2012; Jellinek et al., 2014). They can deal with both qualitative and quantitative data and consider uncertainty intrinsically (Adriaenssens et al., 2004, Kuhnert et al., 2010). Hence, BBN models can be parameterized using information from literature reviews, monitoring efforts and based on scientists and other stakeholder opinions (or beliefs). This is an advantage not only where data is incomplete but also where incorporating LIK is important (Olsson et al., 2004; Carpenter et al., 2006; Mantyka-Pringle et al., 2017).

BBN models provide an integrated framework to structure specific scientific problems and explore future scenarios by graphically representing systems as interactions between clearly displayed variables called nodes (McCann et al., 2006; Landuyt et al., 2013; Smith et al., 2018). The simple graphic structure and ease of modification provide transparency, easing understanding and interpretation by users, making them well suited for participatory modelling and may facilitate acceptance of results by various partners (MacKinson, 2000; Aguilera et al., 2011; Düspohl et al., 2012; Saliou et al., 2017).

Graphical BBN is considered particularly efficient when modelling uncertain and complex issues associated with stakeholder involvement (Maskrey et al., 2016; Salliou et al., 2017; Xue et al., 2017) as it provides a transparent system to engage partners in complex management and decision-making processes (Xue et al., 2017; Kim et al., 2018). Being well suited for integrating data of different types and forms (Holzkämper et al., 2012; Landuyt et al., 2013) and for exploring the diversity of partners' representations of the system at hand (Salliou et al., 2017), graphical BBN has many characteristics advantageous for environmental modelling and knowledge integration (Uusitalo, 2007; Carriger and Barron, 2011; Hjerppe et al., 2017).

A recent advance is the ability to link BBN models with spatial data to incorporate spatial relationships directly into the model structure and spatially map features of the model outcomes at a per-pixel level (McCann et al., 2006; Landuyt et al., 2013; Landuyt et al., 2015; Chee et al., 2016; Smith et al., 2018). The ability to spatially visualize results facilitates communication with non-experts and means that there is enormous scope for possible applications of BBN models in natural resource management (Voinov and Bousquet, 2010; Chen and Pollino, 2012; Douglas and Newton, 2014). The ability to explore mapped outcomes of different scenarios can be made available through GIS web interfaces to partners at different levels - including the local level, where the livelihood decision that ultimately determines the outcome of different policies and interventions is made. In addition, BBN's can also assess temporal changes by running the model across a given time frame.

The success of environmental management generally depends on the acceptance and commitment of partners toward the chosen policy and measures of implementation (Verweij and van Densen, 2010; Jones et al., 2011; Haapasaari et al., 2012). By increasing the transparency of the process and enhancing the mutual understanding among different parties, participatory modelling, including through BBN models, can accelerate decision-making and improve implementation success (Voinov and Bousquet, 2010; Voinov et al., 2016). Ultimately, BBN model products that combine scientific data and knowledge with LIK to explore implications in future scenarios and across the landscape can be put in the hands of users and decision makers through mobile phone technology to promote informed decision-making at all levels (Nielsen et al., 2018; May et al., 2019).

3. How BBN models work

Bayesian networks combine probabilistic and graph theories (Aguilera et al., 2011). They are represented as multivariate, acyclic, and directional causality networks. Probabilistic statistics differ from frequentist statistics, generally used in most research, by their probabilistic and inferential approach (Ellison 1996). In probabilistic statistics, parameters are not considered to have a fixed value with a confidence interval. Instead, parameters are considered random and are described by a probability distribution. Bayes' theorem infers a posterior probability distribution for a parameter using prior knowledge and likelihood together. Hence, in Bayesian statistics, LIK can inform prior knowledge. Girondot and Rizzo (2015), for instance, used LEK about turtle nesting phenology as prior probability distributions in combination with experimental data as likelihood distributions. Bayesian estimation, with informative priors, have found to be superior with small samples compared with maximum likelihood estimation (e.g., Hox et al., 2014).

BBN models represent systems as probabilistic influence networks constituting a network of interactions between variables from primary cause to outcomes with all cause-effect assumptions made explicit. As probabilistic models, BBNs explicitly address interactions between variables (so-called 'nodes') and uncertainty to examine how all possible values of variables may influence the outcome. BBN models assume that the system under study can be described through a directed acyclic graph (i.e., no feedback loops), where each variable is conditionally independent of its non-descendants given its parent variables (i.e. local Markov property). Causal effects are addressed as links between specified nodes that can represent ecological or development factors that influence the likelihood of specific states arising – the causal effects of specific management strategies, for instance (Oliver and Smith, 1990; McCann et al., 2006; Smith et al., 2018).

The BBN model links nodes using Conditional Probability Tables (CPTs) according to hypothesized causal relationships (so-called 'edges'; signified by arrows connecting the nodes). The strength of relationships between variables is defined in the CPTs attached to each node. CPTs specify the degree of belief (expressed as probabilities) that the node will be in a particular state given the states of the parent nodes (nodes that directly affect the node). Evidence is entered into the BBN by substituting the a priori beliefs of one or more nodes with observation or scenario values. Through belief propagation, the a priori probabilities of the other nodes are updated using Bayes theorem. Hence, model outputs can be explored as interactions between clearly displayed variables, providing users transparency and promoting system learning. Notably, BBN models do not test hypotheses about effects but provide a framework for reviewing multiple outcomes in different management strategies and evaluating how sensitive the outcome is to different scenarios (Johnson et al., 2014).

Good practice in the construction, testing and application of BBN models is essential, as is awareness of the modelling approach's purpose, capabilities, and limitations. Several guidelines have been developed (Cain, 2001; Bromley, 2005; Pollino and Henderson, 2010), and according to Chen and Pollino (2012) and others therein, essential steps include:

- Clearly defining the model purpose and the underlying assumptions

- Clear description of network construction and CPT data procedures
- Thorough evaluation of the model and its results
- Transparent reporting of the whole modelling process, including its formulation, parameterization implementation and evaluation

In the context of natural resource management, stakeholder consultation is furthermore essential to ensure that the results are accepted, and that any management plan produced as an outcome is followed (Cain, 2001).

4. Example – a BBN for the coastal halibut fisheries in West Greenland

As an example of a BBN model, we developed a BBN model describing the costal halibut fisheries in West Greenland. This model (as well as two previously developed BBN models) constructed in the online *surBayes* application constitutes an implemented tool for presenting and enabling participants in the CAPARDUS research school to develop and play with concrete BBN models. We followed a series of iterative steps modified from Jackman et al. (2006) in developing the BBN model. These include:

A. Defining model purpose

B. Specifying the context and conceptualizing the system

C. Constructing the network structure

D. Parametrizing the model through surveys

E. Visualization of model inferences

F. Model evidence and scenario evaluation

In the following sections, we will briefly describe these considerations in turn.

A. Defining model purpose

The overall objective of the model is to illustrate the potential and use of BBN models, and the model is, as such, a preliminary model more than a final product. The proximate objective is to describe the coastal halibut fisheries in West Greenland and to enable evaluation of the impact of policy interventions on the outcome measures – fisher household income and halibut numbers. In describing the system, we differentiate between the coastal and offshore components and between the system's governance, socioeconomic and environmental aspects. We consider equipment support, landing capacity, coastal standards, market demand, MSC certification and climate change as switches that can be applied to explore future scenarios (see Table 1, section 4). However, the objective is not to explicitly explore the consequences of the report of the fisheries commission issued in 2021 and hence after the commencement of this project.

B. Specifying the context and conceptualizing the system

Greenland's fisheries sector accounts for 80–95% of the country's export income (Mortensen, 2014; Economic Council, 2017; Jacobsen, 2018), and Greenland halibut (Reinhardtius hippoglossoides), account for 30% of Greenland's fisheries export income (Economic Council, 2017).

The halibut fishery is divided into coastal and offshore sectors, which are spatially separate, targeting different stocks and have different management and social-economic contexts (Jacobsen, 2018). The coastal fishery accounts for the greatest proportion of the halibut catch (Petersen and Zeller, 2001). In 2017, Greenlandic vessels landed 38,192 tons of halibut, of which 24,790 tons were caught coastal and 13,402 tons offshore (Ministry of Finance, 2018). There are an estimated five times more small-scale fishing vessels than registered, large-scale vessels (FAO, 2004).

Since 1979, Greenland has gradually been taking over the political decision-making from Denmark. In 2011 the Greenland Ministry of Fishing, Hunting and Agriculture formulated a new regulation (Greenland Self Government, 2011) that introduced an ITQ system for the coastal Greenland halibut fishery that had hitherto been regulated on an Olympic basis as free fishing by everyone until the shared quota was caught (Jacobsen, 2013; Jacobsen and Delaney, 2014). Over a thousand licenses were granted to small entities such as dog sledges, dinghies, snowmobiles and boats of cutter size, reflecting a fishery with a large number of participants and interests. The stated goal of the regulation was to secure biological sustainability and increase the profitability of the fishing fleet by reducing the number of participants (Greenland Self Government, 2011. The means was 1) an ITQ system whereby entities over 6 meters were granted ITQs and 2) a closure of new access to the fishery conducted by entities under 6 meters. The common Total Allowable Catch quota (TAC) was to be divided between these two segments through a fixed allocation key (Jacobsen and Delaney, 2014). As a result, those who had fished under a shared license could no longer fish from 2012, and small-scale fishers lost a supplementary, yet vital, source of cash income needed for their mixed economy. The closure of the fishery for new entrants means that younger men coming into the fishery had to wait to be able to fish independently or not fish at all, with no foreseeable alternative means of employment (Jacobsen and Delaney, 2014).

Specific to the halibut fishery, a halibut management plan has been in place since July 2016 (MFHA, 2016), and the Greenlandic offshore fleet obtained Marine Stewardship Council (MSC) certification in May 2017 (Capella et al., 2017). The coastal halibut fishery has not obtained MSC certification, but it is considered essential to gain access to the lucrative European market and to comply with the corporate responsibility goals of the two leading retailer companies – Polar Seafood and Royal Greenland (Jacobsen et al., 2018; Long and Jones, 2021). However, the fact that the costal halibut fishery has experienced declining CPUE and fish length in some locations, including Disko Bay (Nygaard, 2019), is blocking that option and will likely continue to do so despite some indication of increase in some stocks (https://www.nafo.int/Science/Science-Advice/Stock-advice). The offshore stock is considered relatively stable, with current levels of exploitation sustainable (Cappell et al., 2017), although the stock is vulnerable to fishing mortality (Froese and Pauly, 2019). In the Davis Strait, the stock biomass declined from the late 1980s to 1994 but increased from 1995 to 2000 and has remained stable until 2019 (Nogueira et al., 2019; Nogueira and Estévez-Barcia, 2020)

The coastal fishery is labour-intensive, employing small vessels with catches landed and processed locally. Nevertheless, coastal fisheries are a vital income source, especially for the

8,000 people living in the smaller coastal settlements, many of whom directly or indirectly rely on fishing (Jacobsen and Raaklær, 2014) and considering that 16.2% of Greenland's population live beneath the poverty line (CIA, 2019).

C. Construction of the network structure

We conducted a (non-systematic) literature review of published studies and reports about halibut fishery in Greenland, including environmental, socioeconomic and governance aspects and its interrelation with relevant other sector activities to inform model construction. Multiple online workshops were then conducted within the project group to select variables and visualize how drivers of change were linked to other variables and the relevant output variables using concept maps. An initial BBN model structure was developed based on project members' opinions representing relevant scientific disciplines and experience and the literature insights. This initial model structure was then presented to and discussed with relevant partners in natural resource management representing scientists and managers of the halibut fishery, industry and users. This led to some adjustments and updates of the model structure to the final version presented in Figure 1, consisting of 29 nodes (Table 1) and 49 edges. However, as mentioned it was not possible to conduct meetings or workshops with representatives of the fishermen's' organizations due to the Corona pandemic (see also below). The workshop 'to promote good practice in the use of local and scientific knowledge for informing natural resource management in Greenland' in Aasiaat 2022 included hunters and fishermen from local communities and representatives from KNAPK, The Greenland Association for Hunters and Fishermen contributing to the discussion of different aspects of the BBN model presented.

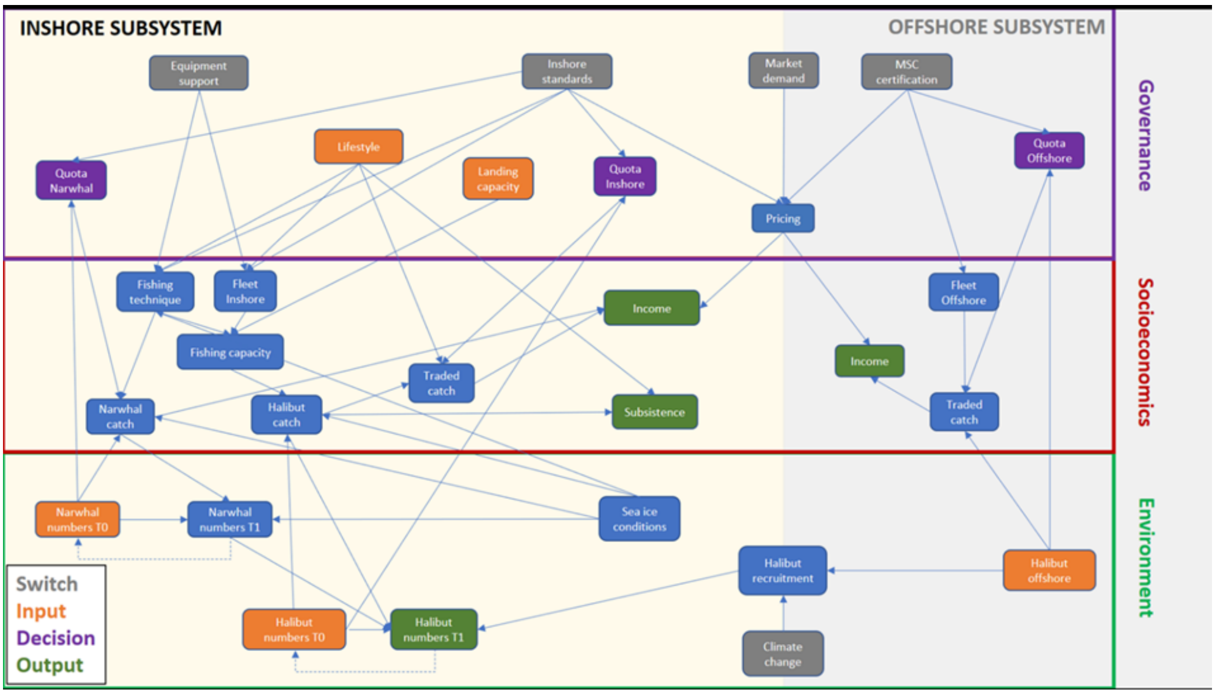


Figure 1. Conceptual model structure for the BBN on coastal halibut fisheries in West Greenland.

Table 1. Nodes included in the costal halibut BBN model, including their grouping and definition/description. Nodes in grey were used as switches to enable addressing 'what-if' scenarios.

Group	Name	Description
Environment	**Climate_change**	the long-term effect of climate change on halibut populations
Environment	Halibut_T0	the population size of the catchable stock (fish >40cm) at the start of a 7-year period

Group	Name	Description
Environment	Halibut_T1	the population size of the catchable stock (fish >40cm) at the end of a 7-year period
Environment	Narwhal_T0	the number of narwhals in the population at the start of a 7-year period
Environment	Narwhal_T1	the number of narwhals in the population at the end of the 7-year period
Environment	Offshore_Halibut	the population size of the catchable stock (fish >40cm)
Environment	Recruitment	the effect of 1-year-old offshore survival on the catchable costal stock seven years later
Environment	Sea_ice	the sea ice conditions, measured in the number of months covered per year
Governance	**Equip_support**	the company-based subsidies and public loans
Governance	Inshore_quota	the total weight of halibut allowed to be caught inshore
Governance	**Inshore_Std**	the political balance between sustainability and income and provision of self-sufficiency
Governance	Landing_cap	the presence of landing facilities in the community
Governance	Lifestyle	the proportion of the households engaged as occupational or recreational fishermen
Governance	**Market_demand**	the external market influence on pricing
Governance	**MSC_cert**	the MSC certification practice, where sustainable harvest and no environmental damage are required
Governance	Narwhal_quota	the total number of narwhals allowed to be caught inshore
Governance	Offshore_quota	the total weight of halibut allowed to be caught offshore
Socioeconomics	Fishing_cap	the total catch capacity
Socioeconomics	Halibut_catch	the total weight of halibut caught inshore
Socioeconomics	Inshore_fleet	the number of people engaged in fishing/hunting
Socioeconomics	Inshore_income	the household income derived from fishing, hunting or other (undefined activities)
Socioeconomics	Inshore_TrCatch	the total weight of inshore halibut traded
Socioeconomics	Narwhal_catch	the number of narwhals caught
Socioeconomics	Offshore_fleet	the total tonnage of trawlers
Socioeconomics	Offshore_income	the number of household incomes that are derived from offshore fisheries
Socioeconomics	Offshore_TrCatch	the total weight of offshore halibut traded
Socioeconomics	Pricing	the per weight prices agreed upon through international negotiations
Socioeconomics	Subsistence	the contribution to the household subsistence
Socioeconomics	Technique	the distribution of harvest techniques/vehicles used in fishing/hunting activities

The model incorporates climate change and offshore catch effects on halibut recruitment (Froese and Pauly, 2019; Wheeland and Morgan, 2019), determining the coastal halibut stock in period T1. The prevailing assumption is that individuals (mainly fry) entering fjords become residents, with limited emigration, particularly from Greenland's northwestern fjords (Boje, 2002). Hence, the coastal populations are considered 'dead-end stocks', although recent research challenges this assumption (Barkley et al., 2018). In this simplified system, halibut stock in period T1 is determined by halibut stock in period T0, the catch in T0 and narwhal numbers in period T1 as the main predator with an impact on halibut stocks (Laidre et al., 2004; Laidre et al., 2005). Narwhal numbers in period T1 are determined by the narwhal stock in T0, which in theory determine narwhal quotes (Nielsen and Meilby, 2014) and hence affects narwhal numbers in period T1. Narwhal numbers in period T1 are assumed to be sensitive to climate change (Laidre and Heide-Jørgensen, 2005, Laidre et al., 2008; Watt et al., 2013; Chamboult et al., 2020) and hence influenced by sea ice conditions, which also influence narwhal catch (Nielsen, 2009; Nielsen and Meilby, 2013) and the coastal halibut fishing techniques applied (Hendriksen and Jørgensen, 2015). Both halibut and narwhal stock in period T1 influence stocks in the next period. In addition, both narwhal and halibut catch create household income (Delaney et al., 2012; Hoover et al., 2013; Hendriksen and Jørgensen, 2015). However, the model incorporates more detail for the halibut catch differentiating between trade and subsistence income. The model assumes that the proportion of the catch traded vs consumed by in the fisher's household or shared in the community (i.e. subsistence) depends on the lifestyle of the fisher (i.e. whether he has a professional or a recreational hunter and fisher license).

Much of what is caught is used for household consumption, and meat and fish also circulate within local distribution channels of sharing and exchange (Poppel and Kruse, 2021). However, the coastal fishery for Greenland halibut, using long lines from small open boats in the summer or from dog sledges and snowmobiles through holes in the sea ice during winter, provides income and employment in production and processing (Andersen and Flora, 2019; Hastrup, 2016; Nuttall, 2017, 2019).

Traded halibut also depend on the coastal halibut quota, which in theory should depend on the coastal halibut stock in period T0 (Jacobsen et al., 2012). Quotas for the Greenlandic fleet are distributed based on historic fishing rights, capacity and through consultation with the Fisheries Council. Scientists at Greenland Institute of Natural Resources (GINR) are responsible for conducting stock surveys and serving as NAFO Scientific Council experts. NAFO is responsible for undertaking halibut stock assessments and delivering TAC advice to Greenland and Canada. This advice is based on data from both surveys and fisheries in the respective EEZs. However, in practice, quotas frequently exceed scientific recommendations and are often raised during the season due to pressure from fishers and the industry's strong lobbying position (Jacobsen et al., 2012; Long and Jones, 2021).

The halibut catch node is determined by the fishing capacity, which depends on the fishing technique applied and the magnitude of the coastal fleet and is influenced by the local landing capacity through individual investments. However, both the applied fishing technique and magnitude of the coastal fleet are also influenced by Self Government subsidies for equipment and the lifestyle of the population (i.e. the distribution between professional and recreational hunters and fishers) and a node called inshore standards, which represents the overall governance structure of the coastal fishery. The inshore standards thus determine quotas and the pricing of halibut. In practice, fisheries management is the responsibility of the Department of Fisheries in the Ministry of Fisheries Hunting and Agriculture (MFHA), operating through the Greenland Fisheries License Control (GFLK), whereas the Ministry of Environment and Nature has little involvement in fisheries management (Long and Jones, 2021). Pricing is also influenced by the market demand for halibut and, in turn, determines the income in both the coastal and the offshore segments. Furthermore, MSC certification, which currently only includes the offshore segment, combined with the magnitude of the offshore halibut stock, determines the price that can be obtained for halibut and the quota for offshore halibut through its requirement for sustainability. Finally, the MSC certification scheme also influences the offshore fleet's magnitude and composition. In addition to the state, the MSC certification, industry and scientific actors play significant roles in the governance structure of the halibut fishery, formally and otherwise (Long and Jones, 2021).

D. Parametrizing the model through surveys

The discrete BBN model was constructed in the online application *surBayes* using a probabilistic approach quantifying the influence of the linkages on each node's state in the CPTs. Ideally, a joint multiple-day workshop with participation from all relevant stakeholder groups would have been held at this point to further discuss and obtain beliefs to parameterize the model. In addition, original project plans included workshops in a selected municipality and community on the West Coast for model verification, input and interpretation of results – i.e., using a face-validity validation procedure (Kleeman et al., 2017). However, these plans had to be abandoned due to continuing and prolonged travel and meeting restrictions associated with the Corona pandemic. Instead, we conducted multiple Zoom meetings with selected partners from the groups, managers, scientists, industry, and users to solicit their beliefs about the governance, environmental and socioeconomic components to parametrize the model. These meetings combined two partners from different sectors – for instance, Greenland Institute of Natural Resources and Royal Greenland – to facilitate discussion and reach a consensus about the influence of the linkages on each node's state. However, this means that the model outcomes and scenario development has not been vetted by the perhaps most important group, fishermen from local communities, and the model is therefore only used for illustrative purposes and the results are thus not valid.

Beliefs concerning each input node were obtained using either the Analytical Hierarchy Process (AHP) (Saaty, 2008) for smaller CPTs (less than 10 unique combinations) or (fuzzy) discrete choice modelling (fDCM) (Aggarwal et al., 2019) for larger CPTs using online surveys as part of the *surBayes* application. The AHP-based survey asks participants to choose, given a specific situation (indicated by the states of other dependent 'parent' nodes), the most likely state among each unique combination of the possible states a node can have and scoring how important that node is in determining that outcome on a scale from one to nine (one indicating equal importance and nine much more important). The fDCM-based survey asks participants for a random subset of the CPT to choose, given a specific situation (indicated by the states of other dependent 'parent' nodes), the most likely state that node will have, and how certain the participant is with its choice on a scale from one to ten (one indicating no confidence (random choice) and ten indicating high confidence (unequivocal choice)). While the AHP answers are directly transformed into CPT vales, the fDCM answer is used to estimate CPT values using multinomial logistic regression. Following up on these meetings and to obtain the beliefs of partners unable to participate in the meetings, questionnaires designed to solicit beliefs about governance, socioeconomic and environmental aspects were circulated to respective groups.

For the input nodes (Halibut T0, Offshore halibut, Narwhal T0, Lifestyle, Sea ice), we used either peer-reviewed studies to determine their CPT-values based on the general conclusions from those studies or used them as 'switches' to allow for contrasting different scenarios and set these to standard values (Climate change, Equipment support, Inshore standard, MSC standard. Landing capacity, Market demand).

E. Visualization of model inferences

The final and parametrized model was used to infer the strength of the linkages between nodes, which indicates the influence nodes have on each other either directly or indirectly throughout the network. Node specificity in their states and sensitivity to changes in the network can be visualized in the *surBayes* tool. This inference through visualization also allows for future testing, calibration, validation and updating of the model, as recommended by Marcot et al. (2016).

F. Model evidence and scenario evaluation

The final model was designed to enable the evaluation of different future scenarios. To do this, 'evidence' can be set for any of the nodes by fixing them to a specific state and after that, rerunning the model to enable updated inferences given the newly defined future situation. We defined three future scenarios linked to the Sustainable Development Goals (SDGs). These included:

- Increased global demand
- Involving the switches "market demand" and "MSC certification" mainly affecting the "price". This scenario is linked to SDG 12 - Responsible consumption and production - as well as SDG 2 - Zero hunger.
- Climate and biodiversity change
- Involving the switch "climate change" affecting "halibut recruitment" and the switch "inshore" standards affecting halibut quotas. These are linked to SDG 14 - Life below water.
- Sustainably regulated communities
- Involves the switches "inshore standards" and "equipment support". These are linked to SDG 11 - Sustainable cities and communities - and SDG 12 - Responsible consumption and production.

Table 2. Overview of proposed states for the nodes that define each scenario.

Global demand	Climate change	Regulated communities
• Market_demand = High	• Sea_ice = Ice_free	• MSC_cert = Yes
• MSC_cert = No	• Landing_capacity = High	• Inshore_std = Yes
• Inshore_std = No	• Fishing_capacity = High	• Offshore_quota = Low
• Equip_support = High	• Offshore_fleet = High	• Inshore_quota = Low
• Landing_cap = High	• Inshore_fleet = High	• Narwhal_quota = Low
• Offshore_quota = High	• Technique = Cutter	• Equip_support = Low
• Inshore_quota = High		

Exploring and refining these scenarios will be one focus of the research school in Aasiaat in 2022. Figure 2 illustrates an output of the model for each scenario compared to the business as usual – i.e., no change outcome. However, as mentioned, these results are only for illustrative purposes and does not constitute valid predictions.

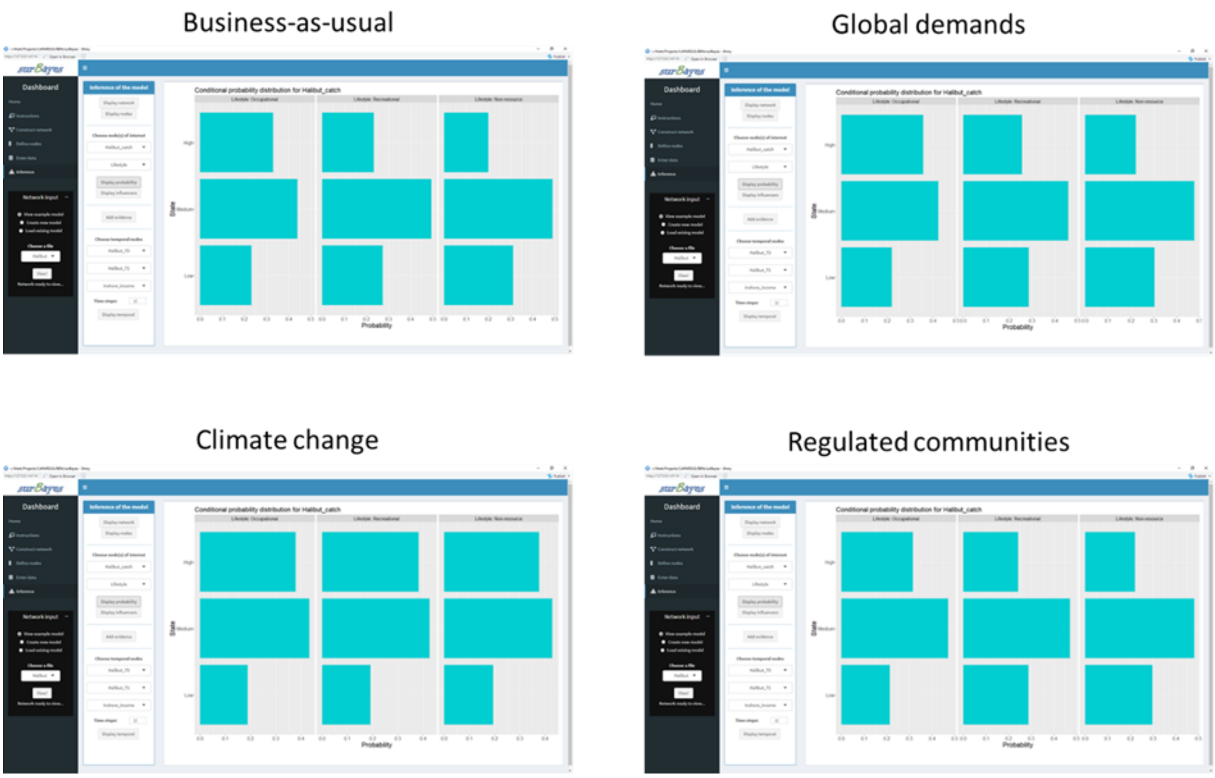


Figure 2. Illustrations of the scenario outcomes compared to business-as-usual. Note that the model is preliminary and for illustrative purposes only, which means that the results and predictions are not valid.

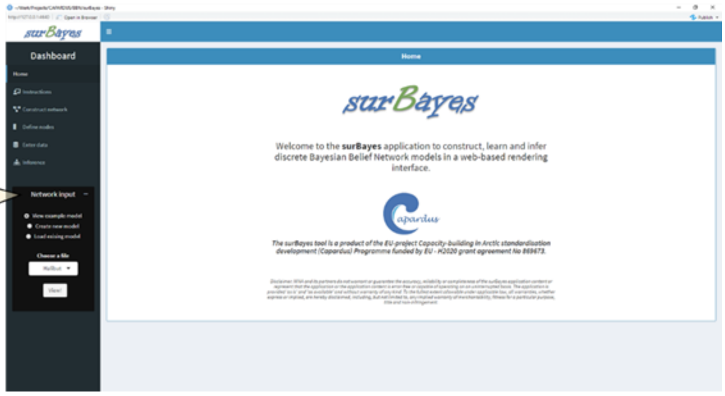
5. 'Cookbook' for constructing a BBN model in surBayes

Below we present a step-by-step guide for using the *surBayes* app.

surBayes app

Welcome to the **surBayes** application to construct, learn and infer discrete Bayesian Belief Network models in a web-based rendering interface.

The first step is to choose either to *View* an example model, *Create* a new model or *Load* an existing model in the left-hand **Network input** box, and confirm. Any changes made in the remainder of the application are only saved to the database when pressing the *Save!* button.

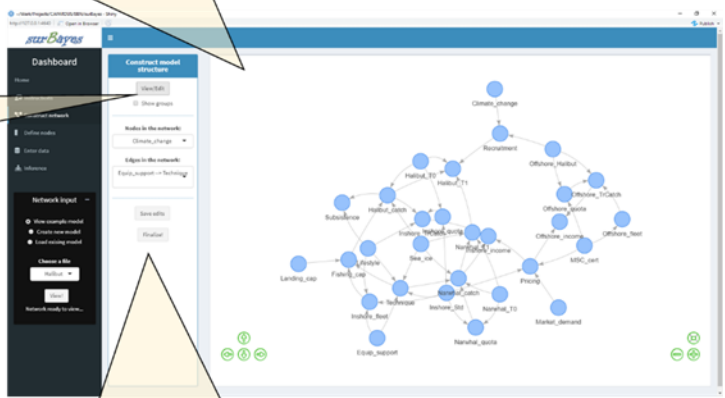


1. Construct network

Once a model has been created, the model structure can be constructed, or adjusted when an existing model has been loaded, by choosing the **Construct network** menu.

In the graphical display, the structure can be edited using the Edit button in the top-left button. Remember to save edits using the *Save edits* button.

The *View/Edit* button allows you to visualize and edit the network. In case groups of nodes have been identified under the next step, these can be highlighted with the checkbox *Show Groups*.



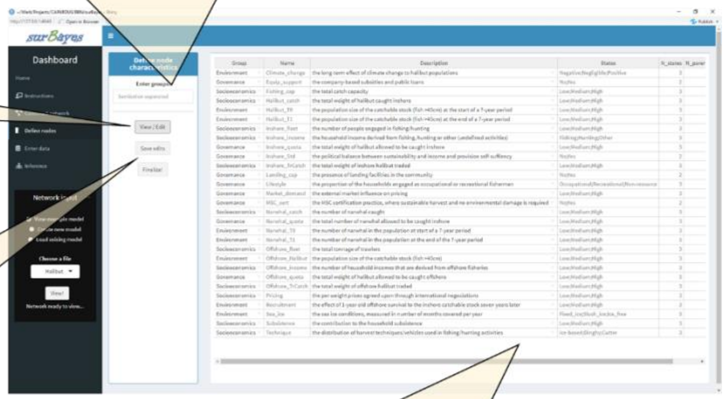
Once satisfied with the network structure, this can be finalized by pressing the *Finalize!* button after which changes are not possible anymore.

2. Define nodes

An overview over the nodes in the network can be viewed by choosing the **Define nodes** menu

By entering group definitions (semicolon separated) into the textbox in the top-left corner, these can -optionally- be added to the different nodes in the table.

An overview over the nodes in the network can be viewed by pressing the *View / Edit* button.



Edits can be saved by pressing the *Save edits* button. Once satisfied with the network structure, this can be finalized by pressing the *Finalize!* button after which changes are not possible anymore.

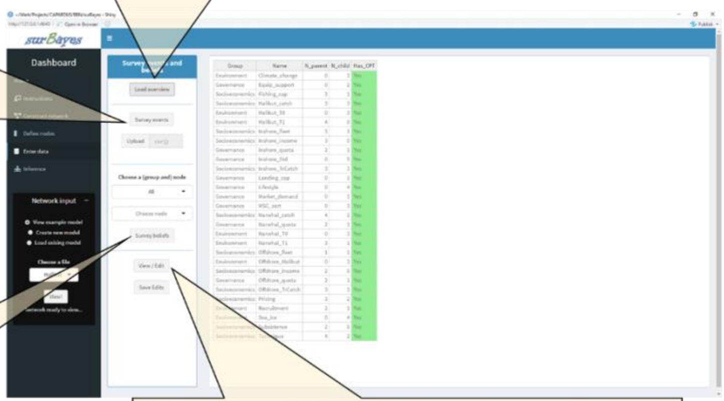
In the table, after having finalized the network structure (previous step), also the node states can be added (semicolon separated), as well as a specific description or definition of each node.

3. Enter data

Once the network structure and nodes have been finalized, the data for the network can be collected in the **Enter data** menu.

By pressing the *Load overview* button, a tabular overview of the nodes and whether they have conditional probability tables (CPT) connected to them.

Individual evidences of the states of the nodes can be obtained either by pressing the *Survey events* button or uploading an Evidences Data file (CSV, semicolon delimited). Surveying events will, depending on the complexity of the model, require a relatively large number of records to populate the network.



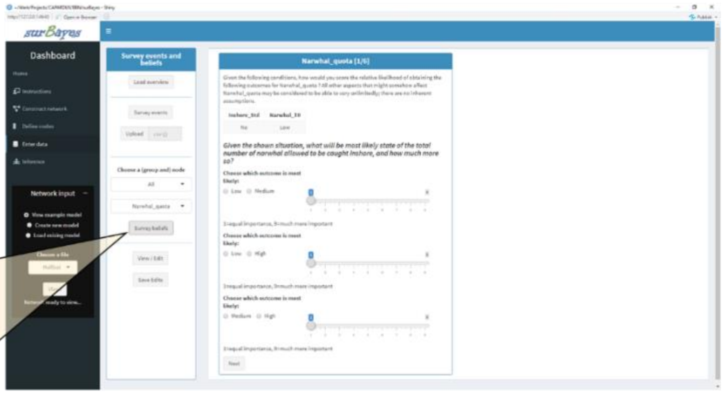
Belief data for each node can also be collected by choosing a specific (group and) node and pressing the *Survey beliefs* button to perform a choice survey.

CPT tables can be directly viewed or entering the required data directly into the CPT tables by pressing the *View / Edit* button. Edits can be saved to the table by pressing the *Save edits* button.

3. Enter data

Once the network structure and nodes have been finalized, the data for the network can be collected in the **Enter data** menu.

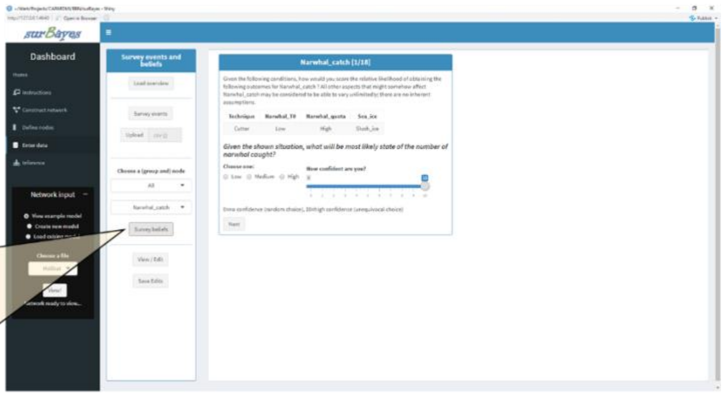
Beliefs concerning each input node were obtained using the Analytical Hierarchy process (AHP) for smaller CPTs (less than 10 unique combinations). The AHP-based survey asks participants to choose, given a specific situation (indicated by the states of other dependent ('parent') nodes), the most likely state among each unique combination of the possible states a node can have and scoring how important that node is in determining that outcome on a scale from one to nine (one indicating equal importance and nine much more important).



3. Enter data

Once the network structure and nodes have been finalized, the data for the network can be collected in the **Enter data** menu.

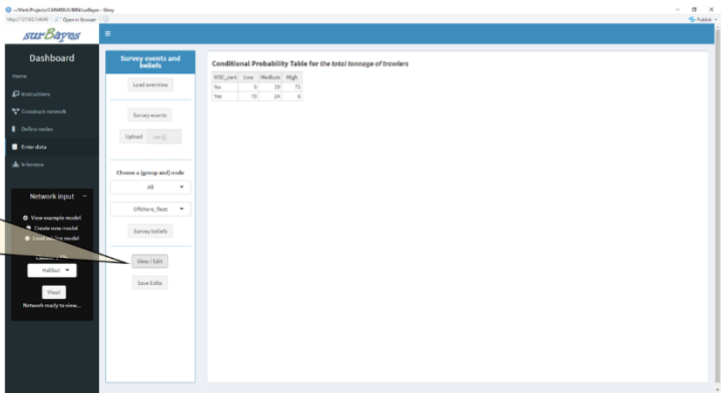
Beliefs concerning each input node were obtained using the (fuzzy) discrete choice modelling (fDCM) for larger CPTs. The fDCM-based survey asks participants for a random subset of the CPT to choose, given a specific situation (indicated by the states of other dependent ('parent') nodes), the most likely state that node will have, and how certain the participant is with its choice on scale from one to ten. The fDCM answer are used to estimate CPT values using multinomial logistic regression.



3. Enter data

Once the network structure and nodes have been finalized, the data for the network can be collected in the **Enter data** menu.

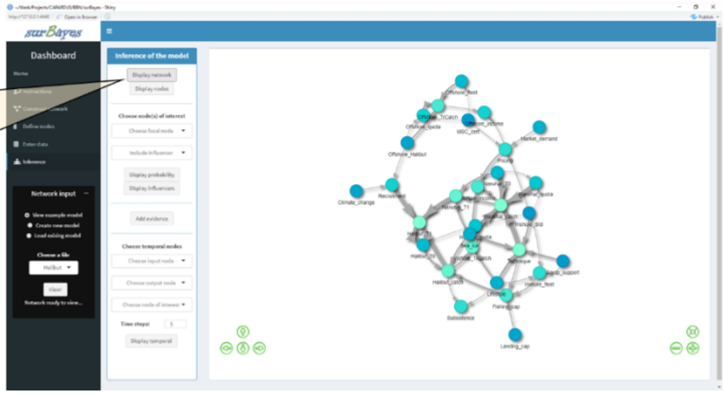
Data, based on for instance empirical statistics, expert knowledge, local knowledge or even opinions, can also be directly entered into a chosen CPT by choosing a node and pressing the *View/Edit* button.



4. Inference

Once network structure, nodes and data are in place, the **Inference** menu allows visualizing the model outcomes.

The network structure can be visualized by pressing the *Display network* button. Also, the characteristics (specificity in their states and sensitivity to change) of the nodes in the network can be visualized by pressing the *Display nodes* button (this process may take some time!).



4. Inference

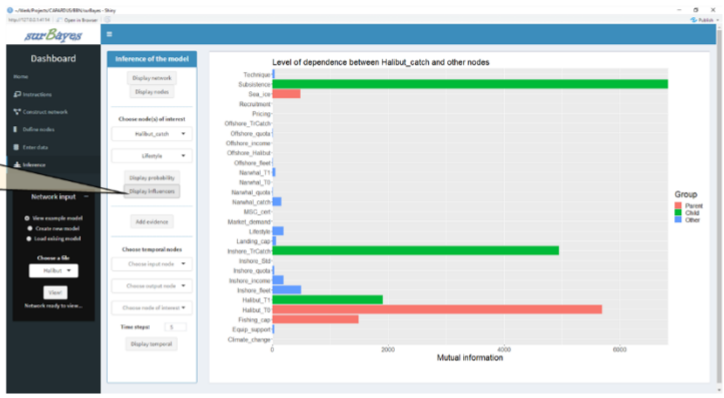
Once network structure, nodes and data are in place, the **Inference** menu allows visualizing the model outcomes.

After having chosen a node of interest in the dropdown menu, also the probability distribution for single nodes can be plotted by pressing the *Display probability* button, either with or without including a node of influence in the plot.

4. Inference

Once network structure, nodes and data are in place, the **Inference** menu allows visualizing the model outcomes.

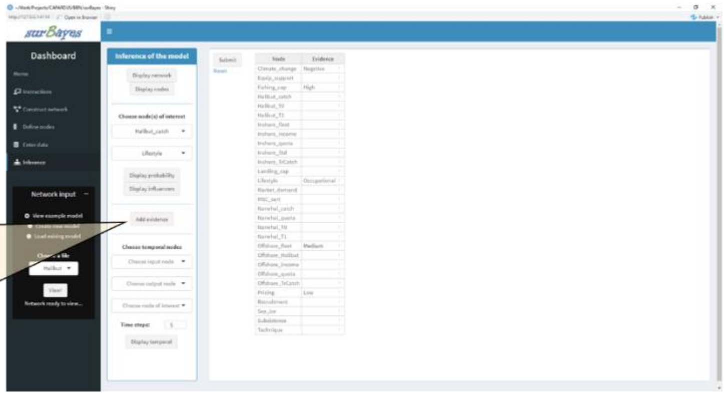
Which nodes have the most influence on the chosen node of interest can be visualized by pressing the *Display influencers* button.



4. Inference

Once network structure, nodes and data are in place, the **Inference** menu allows visualizing the model outcomes.

To assess various 'what-if' scenarios, evidence can be set by pressing the Add evidence button. In the tabular overview over nodes, the state of various nodes can be set. By pressing the *Submit* button, these changes are applied to the network. Renewing the displays show the adjusted outcomes. The network can be returned to its default by clicking the *Reset evidence* link.



4. Inference

Once network structure, nodes and data are in place, the **Inference** menu allows visualizing the model outcomes.

Finally, in case the network includes a temporal component including an input node (no parents) and output node (no children) that have the same meaning and states, these can be chosen from the dropdown menu, including also a node of interest to plot, and after setting the number of time steps (a number between 1 and 10) the temporal changes to the node of interest will be visualized by pressing the *Display temporal* button.

6. Standards for promoting inclusion of LIK in BBN models

There are approximately 370 million indigenous people on earth (United Nations, 2009), and indigenous people have rights to or manage at least 37.9 million km^2 of land from the tropics to the poles (Garnett et al., 2018). Hence, LIK abounds (Ferguson et al., 1998; Krupnik et al., 2010; Weatherhead et al., 2010) and with a growing focus on evidence-based practice in natural resource management (Sutherland and Wordley, 2018) incorporating resource users' knowledge and perspectives into management decisions is increasingly promoted at a global level (Danielsen et al., 2021). The 196 countries that have ratified the Convention on Biological Diversity (CBD) are, for instance, obliged to respect, preserve, and maintain the knowledge of indigenous and local communities (UNEP, 2012). And the 18th strategic goal of the CBDs Aichi goals specifies that indigenous and local knowledge should be "fully integrated and reflected in the implementation of the Convention" by 2020. Also, the Arctic Council has made repeated calls for the acknowledgement and, where possible, the inclusion of local or indigenous knowledge in environmental monitoring and biodiversity conservation (Thornton and Sheer, 2012; Meltofte, 2013; Danielsen, 2014). Communities in the Arctic and elsewhere also seek a more significant role in decision-making and harvest regulation for resources they depend on (Amos and Turner, 2018).

Hence, there is growing recognition of the need to engage with and utilize LEK in a more comprehensive and meaningful way when conducting assessments of environmental change and making environmental decisions from local to global scales (Ford et al., 2016 a,b; Gustafsson et al., 2019; Obermeister, 2019). Drawing upon diverse knowledge systems will arguably improve our understanding of social-ecological interdependencies, promote innovation, and contribute to the identification of desirable pathways for the future (Tengö et al., 2014). Incorporating local knowledge in environmental management furthermore increases legitimacy and builds trust in decision-making (e.g., Fazay et al., 2006; Berkes, 2009; Tengö et al., 2014; Mistrey and Berardi, 2016). However, key challenges remain in connecting information generated by different knowledge systems for informing management (Game et al., 2018; Tengö et al., 2017; Tomaselli et al., 2018). Moreover, validation across knowledge systems is a significant challenge (Tengö et al., 2014). Current science-based land management systems may, for instance, not effectively include indigenous and local perspectives (Dallman et al., 2011; Tengö et al., 2021). As a result, LIK is not consistently quantified or used in broader decision-making (Sejersen, 2003; Johnson et al., 2015).

Indigenous and science-based knowledge systems are complex and diverse yet increasingly intertwined (Agrawal, 1995). However, previous work illustrates that natural resource management and decision-making in many locations' rests on a scientific and bureaucratic framework of resource management that poses significant barriers to the meaningful inclusion of indigenous views and knowledge (Usher, 2000; Nadasdy, 2003; Menzies and Butler, 2006; Sandlos, 2007; Henri, 2012). Much research and management efforts claiming to use indigenous knowledge have reduced it to anecdotal information separated from its source and context. Considerable research efforts have also focused on scientific validation of indigenous knowledge systems, in the process compromising the integrity and complexity of the knowledge (Bohensky and Maru, 2011; Gratani et al., 2011), according to some observers, promoting power inequality between technocrats and communities (Nadasdy, 1999; Bohensky et al., 2013). More recently, local partners have been increasingly involved in monitoring and modelling efforts undertaken by scientists. However, their roles have often been limited to data provision, such as monitoring observations (Bélisle et al., 2018).

However, participatory modelling approaches, including co-developing BBN models, can draw on the subjectivity that is already inherently involved in modelling. Models are simplified representations of a complex reality, and modelers already make judgement calls to decide what component of reality is to be represented, what parameters are most relevant and what level of complexity is necessary (Krueger et al., 2012). This inherent subjectivity makes modelling especially appropriate to combine different forms of expertise arising from scientific and LIK (Barber and Jackson, 2015). While scientific ecological knowledge generally arises from hypothetico-deductive approaches, LIK stems from the direct contact of people with their environment. According to Bélisle et al. (2018), this has benefits in the sheer exposure to the processes in question, enabling LIK to reach a precision level that is virtually impossible to match with fieldwork conducted over a few weeks and based on limited sample size. Hence, LIK may be used to build the conceptual framework behind a model, set the scope, limits, and assumptions, and validate model outputs (Krueger et al., 2012). These are all options that are feasible to exploit in BBN models. Models based on LIK are likely to be particularly valuable in sustainable use contexts when local partners are utilizing wildlife or fish resources of high economic value and when they simultaneously have a major stake in the management of this resource (Cyler et al., 2000).

Nevertheless, several challenges exist to the fruitful use of LIK in natural resource management that also apply to the co-creation of BBN models. These include basic differences in language but also more complex differences in worldview that can hinder communication and mutual understanding (Berkes, 2012). A central consideration is, furthermore, that "knowledge itself is power" and that those who share knowledge should not lose power in the process (Nadasdy 1999). Knowledge is also inherently dynamic, involving the constant evolution of knowledge-based resources and processes for governing those resources (van Kerkhoff and Szleza, 2016). Compared with western-based science, indigenous and local knowledge systems represent alternative ways of learning from and with the environment through close and continuous observation framed by distinct worldviews with strengths and limitations (like all knowledge systems) (Johnson et al., 2015). Knowledge systems can be viewed as networks of actors connected by formal and informal social relationships that dynamically combine doing, learning, and knowing (van Kerkhoff and Szleza, 2016). Indigenous and local knowledge, similar to scientific knowledge, is produced in the context of power relations. It is not equally distributed. Some knowledge may be considered the domain of specialists or persons of specific positions and/or gender (Cash et al., 2003; Hill et al., 2012). Therefore, careful consideration of representation is needed about who is considered the spokesperson(s) of LIK systems, how they are appointed, and what forms of representation are allowed for and enabled in science-policy processes (Voß and Bornemann, 2011; Beck et al., 2014). Furthermore, some knowledge holders have highlighted that removing their name from the context is the equivalent of removing a citation as it may strip away the information's credibility and diminish the associated community's right and access to that collective knowledge (Wheeler et al., 2020).

There are few examples of BBN model processes explicitly incorporating CBM observations or LIK more broadly, particularly in an Arctic context. However, recommendations from participatory modelling approaches and shared decision-making may also apply here. These include promoting transparency in framing the decision-making problem and the evaluation criteria and logic to reduce confusion and conflict and support better collaboration (Cummings et al., 2018). These recommendations also apply to the creation of BBN models, and approaches to explicitly incorporating different values of multiple partners into decision-making using BBN models are being developed (Laurila-Pant et al., 2019).

The framing of the decision process and the conceptual model should be based on concepts important to local perceptions and understanding rather than western preconceptions (Lideloff et al., 2009). This includes, for instance, the concept of "season", which may entail a very different understanding of the time of year between western and indigenous cultures (Lideloff et al. 2009). Various conceptual and terminological shortfalls may be overcome by replacing the standard BBN model network representation with more graphical representations where nodes are represented by images indicating the current state of each node. Lideloff et al. (2009) experimented with linking a BBN model of aboriginal knowledge about wetland ecology in Australia with a knowledge database that allowed additional information to be recorded about every node, node state and interactions between a node and all influencing parent node states. This level of information effectively provided a full narrative of the state of the model as either text or sound files on a web page, allowing users to better explore the model and gain a detailed understanding of the LIK behind the model in words and language used by the developers of the model (Lideloff et al., 2009).

However, while such information provides a more detailed representation of the BBN than the network diagram alone, it does not clarify the intellectual property held in the parameterization of the BBN. Lideloff et al. (2009) suggested that one approach to solving this problem is to develop two parallel models – one by indigenous knowledge holders and one by western scientists – and then have each group appraise the other group's model. This would highlight the areas considered most important by each group and foster discussion about the relative differences in understanding.

Danielsen et al.'s (2014) experience with focus groups in Greenland suggests that solicitation of knowledge for creating a BBN model should be undertaken as an open learning process, where community members participate directly with the right to vote and express opinions. In Danielsen et al.'s approach, community members were gatekeepers detecting and deciding which data were complete and which were false or out of context and, therefore, should be discarded. Danielsen et al.'s and others' (Stephenson and Moller, 2009; Huntington, 2011) findings suggest that community members' ownership of the data and information and their control over the knowledge, the validation process, and the application of the knowledge is critical to their sense of empowerment.

Furthermore, when modelling aims to assist decision-making, it is critical to ensure that the information provided by the model output is communicated and interpreted unambiguously by both the analyst and the decision-maker (Cartwright et al., 2016). Software for the estimation BBN models, including *surBayes*, provides plenty of analytical opportunities and options for a visual and interactive presentation, promoting communication to different types of actors (Henriksen et al., 2007; Smith et al., 2018). However, it is the analyst's responsibility to avoid misinterpretation of the output, and the user should attentively keep track of all the settings made in the model and consciously inform decision-makers about the scenario that the model represents at any particular moment (Laurila-Pant et al. 2019). Some BBN models, including spatial explicit BBN models, can be accessed and used by non-professionals through online map applications (Spaciano et al., 2021). This requires being very clear about the risks if the tool is improperly used—for example, by running the model if assumptions are not met (e.g. Cyler et al. 2000) and describing how to interpret the output. Such applications also risk exacerbating power inequalities if access to the relevant platforms and data management systems is difficult in remote regions or not culturally appropriate (Johnson et al., 2021).

Tengö et al. (2014 and 2017), based on the Multiple Evidence Based (MEB) approach suggest five tasks to guide respectful collabora¬tions between knowledge systems. The first – to mobilize – emphasizes articulating LIK for sharing, using culturally appropriate methods. This step is required because LIK may not be visible directly as knowledge and may be marginalized or in decline. Hence, revitalizing, assessing relevance and validation using mechanisms within the knowledge systems involved may be required and is often a core objective in Indigenous-people-led initiatives (Tengö et al., 2017). The second task – to translate – concerns making sure that different knowledge contributions make sense to representatives from different knowledge systems. This requires that scientific knowledge is understandable to representatives from LIK systems and that LIK and its different dimensions are understandable to researchers to enable mutual understanding of respective contributions. This implies communication using a language and terms that can be understood by all actors and clarifying knowledge claims or criteria of credibility respectfully (Tengö et al., 2017). The third task is referred to as negotiation and involves joint assessment of convergence, divergence, and conflicts across knowledge contributions. This should include representatives from the knowledge systems in analyzing and negotiating whether the contributions are overlapping, converging, or diverging (Tengö et al., 2017). This should acknowledge that some aspects might be in disagreement, potentially stemming from incommensurable aspects of different knowledge systems (Tengö et al., 2017). But also requires awareness of the dual role of actors, including scientists, as experts and carriers of knowledge as well as partners with vested interests and representing or possessing different levels of power (Tengö et al., 2017). The last two tasks involve synthesizing and applying the knowledge. To synthesize entails shaping a broadly accepted common knowledge that maintains the integrity of each knowledge system by braiding the strands of knowledge rather than integrating aspects of one knowledge system into another (Tengö et al., 2017). And applying means using the produced common knowledge bases to make decisions and take actions relevant to all involved actors (Tengö et al., 2017).

Overall, these and other studies (e.g., Tomaselli et al., 2018) suggest the following recommendations:

- Carefully consider the identification and selection of key knowledge holders, taking into consideration differences in knowledge holding, and determine the level of their representation using purposeful sampling and thematic saturation to define the sample and its size

- Create a respectful collaboration process between scientists and knowledge holders to facilitate mutual learning and empowerment and where LIK holders retain ownership of the data and information and control over the knowledge, the validation process, and the application of the knowledge

- Facilitate mobilization of LIK. This could also involve using triangulation or other approaches to validate LIK quality (but not in comparison to scientific or other knowledge) – i.e. conducting multiple group discussions or consultations and individual interviews to ensure the reliability of both quantitative and qualitative input to the BBN model construction (this involves aspects of negotiation)

- Be transparent and inclusive in framing the scope and objective of the BBN model and use concepts important to local perceptions and understanding (i.e., involves aspects of translating), focusing on problems and solutions of relevance to local communities. Ideally, the information provided by the model output should be interpreted unambiguously by both the analyst and the communities

- Involve knowledge holders in the overall model design and the analyses and interpretations of the findings by presenting to and discussing each step along the way (i.e. negotiation and synthesis) with study participants to avoid misinterpretation
- Produce tools operationalizing technical models accessible to communities (i.e. apply) and be very clear about the risks of misconception if the tool is not used appropriately
- Explore options for making the underlying LIK in the BBN model explicit and viewable to the user acknowledging LIK intellectual property rights

Further avenues for research:

- Explore how observations are discerned from inferences, how knowledge is created from observations
- Whether and how knowledge is shared within a community, including transmission processes from one generation to another, and how individual experiences and interactions with other cultures change a knowledge system

7. Required ethical considerations for the use of BBN models with LIK

Western scientific use of LIK and engagement with indigenous communities have been criticized by Indigenous commentators (Liedloff et al., 2009). Often conventional western science methodologies do not leave Indigenous participants in collaborations with scientists feeling a sense of ownership of the process and final products (Liedloff et al., 2009). Efforts to integrate Indigenous and science-based knowledge systems for co-management of wildlife have, in some cases, led to the decontextualization and compartmentalization of Indigenous knowledge through its translation (and distortion) into forms that can be incorporated into existing management bureaucracies and acted upon by scientists and resource managers (Cruikshank, 1998; Kendrik, 2000; Peters, 2003; Spak, 2005). Schemes for involving Indigenous peoples in environmental research and decision-making have notably also been criticized for reducing Indigenous knowledge systems to a collection of mere factual data about the environment, thus failing to acknowledge the value system and cosmological context within which this knowledge was generated and within which it makes sense (Simpson, 2001; White, 2008). Knowledge instrumentalization and cultural appropriation is an ever-present concern (Oguamanam 2008) that may perpetuate power inequalities, particularly in attempts to validate a knowledge system through the lens of another (Asselin 2015).

In addition to these insights, a range of ethical guidelines for conducting research with indigenous peoples are applicable and should be adhered to (Nielsen et al., 2021). Of particular relevance to the inclusion of LIK in BBN models these may include:

- Consult with all relevant regional, local, and/or indigenous institutions about the proposed research, inquire about previous and ongoing community research and priorities, and collaborate appropriately. This includes initiating community contact as early as possible, identifying community representatives and striving to build meaningful relationships based on good faith and partnership.

- Adhere to local and Indigenous traditions, customs, and locally adopted research guidelines, permitting requirements, or specific protocols. This includes learning about the region's history, cultures, languages, community perceptions of past and current research conducted in the region, and organizational structures, practices, values, and institutions.

- Seek approval from various entities and informed consent from participants. This requires a description of the research in a plain and local language that discloses methods, sponsors, purposes, and objectives.

- Ideally, the research project should be co-developed by determining the objective and boundaries of the BBN model in collaboration with the community, but as a minimum, ensure that it addresses problems significant to the communities and participants. Developing and presenting the research plan, make sure to address community concerns and expectations for the project. Provide structures for shared decision-making. Be aware and respectful of indigenous peoples' practices and protocols for accountability.

- Determine and enable the appropriate level of community involvement (to both the community and the project) in all stages of developing and implementing the BBN model – including design, analysis, and interpretation. Make all efforts to provide communities and participants information to make informed choices regarding their involvement and contribution to the research. Keep communities and participants informed about research progress and results throughout the research. Include community involvement in all phases of the research effort.

- Determine and describe clearly and in advance who collects, owns, manages, evaluates, and disseminates the data and the privacy rights in relation to beliefs entering into the creation of the BBN model. A clear understanding of data ownership and how data will be treated, including with regard to the anonymity of respondents, allow projects to proceed with a shared understanding of data governance and ownership. Guarantee and uphold anonymity if desired by respondents. Identify potentially sensitive data and observations with individuals and/or the community and establish measures to reduce the likelihood of any harm to individuals or the community.

- Time research activities to avoid disturbing participating community members and knowledge holders during peak hunting, fishing, harvesting, gathering or other seasonal activity periods.

- Present research outputs to local communities in plain and, if possible, the local language using appropriate and effective means of communication. Research participants should have the right to review all products to ensure they have been represented correctly before publicly disseminating them. Researchers should inform how they are used and share all products with participants. Indigenous concepts or words should be written, and orthography is used in publications with explanations in other languages.

- Include an assessment of the feasibility of implementation and the long-term sustainability of research recommendations within the community. Provide assistance in affecting policy implementation of research recommendations.

- Disseminates research findings while respecting confidentiality and designs dissemination strategies involving community partners for both academic and community-level distribution (newsletters, videos, lay publications, TV, and radio). The research participants should be accredited in publications, lectures etc.

These recommendations are based on and modified from various sources (ITK and NRI, 2006; American Anthropological Association, 2012; IARPC, 2018; Rink and Adler Reimer, 2019; IASSA, 2020). Several of these are guidelines developed by indigenous organizations themselves and these guidelines have generally all been vetted by indigenous organizations and their constituency themselves.

8. Promoting the use of BBN model outcomes in Greenland's natural resource management

How to connect information generated by different knowledge systems to inform natural resource management remains a key challenge (Tengö et al., 2017; Game et al., 2018; Tomaselli et al., 2018). Moreover, literature describing how to best promote the use of LIK informed BBN models by government administrations for natural resource management appears very scant, especially in an Arctic context. However, some valuable insights may be gained from studies describing the experience of community-based monitoring (Danielsen et al. 2014), and a community-based muskoxen harvest calculator in Greenland (Cyler et al., 2020) as well as a publication providing an overview of community-based monitoring systems (Danielsen et al. 2021) and about connecting top-down and bottom-up approaches in environmental observing (Eicken et al., 2021).

Danielsen et al. (2014) report on the conception and implementation of a community-based monitoring system in Greenland and describes that the objective from the government's perspective was to encourage data-informed decision-making on natural resources on the part of the local authority and the communities and that it was devised in the face of severe constraints on the governments capacity to monitor natural resources. However, these efforts should perhaps also be seen as a product of mounting frustration among community members and limited local understanding and acceptance of government decisions due to discrepancies between the authorities' perceptions of the status of the environment and that of the local people (Sejersen, 2003), driving the government to want to increase the involvement of users in decision-making. The system builds on quarterly discussions of selected natural resource trends and the likely causes based on users' recorded observations. Based on these discussion Natural Resource Committees (NRC) propose management options (e.g. changed quotas, time and area closure and gear restrictions) to the Settlement Council, who then pass these along the chain of communication to the Local Authority and then the Central Government. In the four communities participating in this pilot project, this led to 14 distinct recommendations for 12 natural resources within the first three years. All institutions along this chain have the option of rejecting the NRCs' proposals. The Local Authority furthermore have very limited decision-making power independent of the Central Government. However, according to Danielsen et al. (2014), the Central Government and Local Authority staff involved in the system provide regular feedback to the communities about their proposed management decisions, whether they had been acted upon or not, and why. Unfortunately, no elaborate discussion or overview of such examples is provided. This could provide important insights into the criteria for Central Government management authorities' acceptance and use of LIK knowledge in natural resource management. However, Danielsen et al. (2014) provide valuable considerations about how the pilot monitoring system could be scaled up to the national level for improved resource management in Greenland. According to Danielsen et al. (2014), this would require establishing "strong linkages" between the local and the national data management systems. What that more precisely would entail remains unclear. However, the Central Government would essentially need to "provide a policy that sets aside government staff time and funds, develop minimum requirements for local monitoring, and establish a data infrastructure system so that locally acquired data, similar to professional scientists' data, could be uploaded, and made publicly available subject to the approval of the data-providing community members". For this to happen would, according to Danielsen et al. (2014), require that there are benefits for both sides. In other words, and focusing here on the administration's use of local data or recommendations, we expect that it would need to substantially reduce management costs (i.e. above implementation costs) or provide other tangible benefits at the central government level, such as filling a data or knowledge gap and perhaps increase local acceptance of management decisions. The latter of these functions could be provided by an appropriately implemented participatory BBN model application, whereas the costs of such a process may not be directly recovered.

Cyler et al. (2020) describe the establishment and application of a community-led harvest calculator for a muskoxen population in Ivittuut as part of the Greenland government's efforts to hand over management responsibility over muskoxen sub-populations to local communities. Evaluating the project, Cyler et al. (2020) emphasized the importance of user-friendly interphase with multi-language support and a model that enabled communities to undertake "what-if" analyses of model projections using their own data. The fact that the model was as simple as possible and easy to parametrize and operate made it accessible to community members, government managers, and scientists and was considered essential for local uptake. The fact that the model enabled the incorporation of community members' own measures of uncertainty in parameter inputs was important for conveying to the local community members the risk associated with different harvest scenarios. These features were considered important for building trust in the model, working interactively with the community through workshops and one-on-one to explain, parameterize, and run the model (Cyler et al. 2020). Cyler et al. (2020) furthermore found that communities provided a wide range of relevant management ideas and were keen to communicate these directly to the central government to reduce delays on the part of the municipal administration. Cyler et al. (2020) describe that government authority and advisory scientist acceptance of data generated by community members at the local level is required for such a model to function. Unfortunately, Cyler et al. (2020) did not elaborate on how this acceptance is achieved but wrote that Arsuk community's request for a quote based on the harvest calculator led to immediate approval of the quota by government wildlife management authorities. In addition, Cyler et al. (2020) recommended that government policy is in place for shared management of wildlife resources and clear rules and procedures, for benefit distribution directly to involved communities and for verification of community wildlife census results. For the acceptance of a participatory developed BBN model, these insights suggest that the model should be as simple as possible and at least partially involve verifiable data or other evidence with the model description provided in a language accessible to administrative staff with a clear indication of uncertainty in parameter input and options for estimating what-if analysis.

Danielsen et al. (2021) further emphasized that monitoring efforts need to be financially viable after end support and provide targeted information that delivers guidance for management. Evaluating a range of community-based monitoring efforts, Danielsen et al. (2021) found that, for approximately the same recurrent government investment, far more interventions result from locally based biodiversity monitoring methods than conventional scientific ones. The greater the involvement of local people in monitoring activities, the shorter the time it takes from data collection to decision-making. The most local and participatory monitoring systems lead to management decisions, which are typically taken at least three to nine times faster than scientist-executed monitoring, although they operate at much smaller spatial scales. These decisions often result in actions based on community rules and enforcement, such as local bylaws governing resource use aimed both at protecting habitats or species and at ensuring a continued supply of benefits for the local communities (Danielsen et al. 2014c). In comparison, monitoring by scientists may be slow in leading to decisions, although the scale of decisions may be very different (Danielsen et al. 2005a).

Eicken et al. (2021) describe a survey of the managers of 30 arctic community-based monitoring programs, which found that many programs inform decisions at the national (40%) and international levels (13%). Arctic CBM programs were furthermore considered to have the potential to contribute to the objectives of ten international environmental agreements, with the United Nations Framework Convention on Climate Change (UNFCCC) (100%) and the Convention on Biodiversity (80%) particularly standing out. It was further argued that Arctic CBM programs contribute to achieving 16 of the 17 SDGs in the Arctic. Furthermore, CBM efforts contributed to better-informed decisions or better-documented processes in key economic sectors in the Arctic region, including hunting or herding (60% of the CBM programs, n = 30), forestry (47%), fisheries (40%), shipping (37%), tourism (37%), and mineral and hydrocarbon extraction (20%). If this is correct, perhaps promoting LIK-informed BBN models in Greenland's natural resource management is, in part, a question of informing government administration actors about the many ways in which LIK already supports the Arctic governments. And in that case, more details about the background for these numbers would be beneficial.

Nevertheless, Eicken et al. (2021) state that mismatches in the aims and missions of government agencies and local entities continue to hamper the ability of management agencies from accessing, understanding, and acting on community-driven observations and their interest in using community guidance (Eicken 2010, Johnson et al. 2015; Lubilo and Hebinck 2019). Despite some progress (Armitage et al. 2011, Kendall et al. 2017, Tengö et al. 2017), both government agencies and academia, according to Eicken et al. (2021), continue to struggle to understand the nature and relevance of CBM and the LIK that informs CBM efforts. Apparent misconceptions include a perceived lack of CBM reliability and failure to appreciate the equivalency of information generated through CBM and by professional scientists (Johnson et al., 2015; Costa et al., 2018). One often observed issue is that CBM typically focuses on phenomena and processes at a scale relevant to communities on a local or at most regional level. In contrast, government priorities are often more aligned with global scales addressing climate or ecosystem scale variables (Eicken et al., 2021). While these phenomena matter to local communities, they may not be as relevant if collected at a coarse scale, and the link to everyday practices may be obscure.

Eicken et al. (2021) also refer to historical power relationships that may create an adversarial dynamic between multilevel actors that are part of co-management or between researchers and community members (Armitage et al., 2011, Long et al., 2016). Furthermore, bureaucratic and political hurdles and a general lack of resources make it difficult for government agencies to rely on CBM for decision support. Finally, international bodies advising governments on resource management are allegedly slow to establish procedures that enable taking CBM observations and LIK into account.

Eicken et al. (2021) assert that part of addressing challenges in using CBM data in top-down management approaches (defined as large-scale programs or high-level frameworks, often driven by governmental action) is to rely on co-design, co-management, and co-production principles. This involves several of the previously mentioned principles for community involvement (cf. above), presumably with a view to community acceptance and continuity or sustainability of the effort. But Eicken et al. (2021) also highlight further development of practices and protocols to allow government agencies, international scientific organizations, and management bodies to incorporate CBM-derived information in their decision-making. How precisely that is to be accomplished in practice is not clear. However, Eicken et al. (2021) suggest tying into existing organizational and governance structures in the area, and presumably, this also means using as far as possible existing data collection tools and approaches and channels of communication. It is further suggested to encourage managers of scientific data repositories to adjust data formats to become receptive to data from CBM programs and to provide focused support for CBM programs keen to connect with scientific data repositories. Finally, Eicken et al. (2021) suggest that great help in overcoming these challenges is to raise awareness about the value of CBM and LIK within government agencies and scientific organizations, including about the usefulness of incorporating information from CBM programs into scientific data repositories in support of systems-level understanding and future decision-making. Providing scientists and administrative staff training on CBM activities and evidence collection from CBM could, according to Eicken et al. (2021), contribute to this objective. And to this could be added training on knowledge creation and use of LIK to inform management decisions, including through BBN models.

Overall, these studies suggest the following recommendations:

- Make visible the data and knowledge gaps where CBM, LIK and BBN models could promote enhanced natural resource management, including reducing cost or effectively supplementing and supporting other monitoring investments and management decisions or providing other tangible benefits

- Show and highlight how CBM and LIK already contribute to and inform management decisions and promote BBN models as a way to increase the transparency and structure better

- Highlight BBN model's ability to incorporate and combine scientifically verifiable data with other forms of knowledge, including based on CBM observations and LIK

- Promote setting aside time and funds for government staff (incl. advisory scientists) to learn about LIK and engage in the development of BBN models

- Involve the government administration as well as communities and advisory scientists in determining the objectives of BBN models and in developing the underlying conceptual model

- Make BBN models as simple and easy to parametrize and operate as possible without scarifying relevance and accuracy to make them accessible to community members and government managers.

- Enable use of locally generated data and incorporate options for addressing uncertainty in parameter inputs in the BBN model to enable assessment of risk, including through scenario analysis

- Conduct workshops and one-on-one meetings with relevant partners to explain, parameterize, and run the BBN model

- Develop and describe the model in detail in Greenlandic, Danish and English

Further avenues for research:

- Explore the administrations, including advisory scientists' arguments for not considering CBM observation and LIK in management decisions and what aspects increase/decrease acceptance of LIK

9. Towards good practice in the use of local and scientific knowledge for informing natural resource management

From November 29th to December 1st, 2022, a workshop to promote good practice' in the use of local and scientific knowledge for informing natural resource management in Greenland was held in Aasiaat, Greenland (see Deliverable 2.3). One aspect workshop focused of the potential role of BNN models to include local and indigenous knowledge in solving natural resource management challenges.

BBN model on inshore halibut fisheries, described in this document, was presented to illustrate how BBNs can describe human interactions with their natural environment (so-called social-ecological systems) and can be used to evaluate the consequences of interventions on the ecological system and human welfare. The workshop further aimed at letting hunters and fishermen from different communities, representatives of Greenlandic authorities, and Greenlandic researchers construct their own BBN model for a specific natural resource management challenge of their choice. This process was performed within four mixed-stakeholder breakout groups in the following manner:

Identify relevant natural resource management challenges in the Arctic
The participants were asked to brainstorm about different resource management challenges in dialogue, agree on a challenge of interest, and, after that, discuss the specificities of this challenge. This included indicating whether the challenge has specific areas and periods of relevance, pinpointing output information that would be of primary interest to them, identifying possible future scenarios relevant to the challenge for evaluation, and assessing its urgency/conflict level.

Construct a social-ecological system network
The participants were asked to construct their own conceptual network illustrating a social-ecological system for their chosen challenge. This was done on paper where they were asked to agree upon which factors should be part of their social-ecological system, which were then noted down as text boxes (so-called 'nodes') and indicate the linkages between these nodes using arrows (so-called 'edges'). Here, only one-way linkages are allowed ('directed acyclic graph'). They were then asked to indicate for each of the nodes whether scientific and/or local knowledge data would be most suitable to parameterize the model for this node.

See BBN models in operation in the surBayes tool
Finally, the participants were invited to play with the available BBN models in the *surBayes* tool to see how such models, when ready, can be used in practice.

Afterwards, the outcomes from the four breakout groups were presented in plenary to consolidate lessons learned. This included their experiences from the group work, the general usefulness of BBN models, and whether this could be an approach to better integrate local knowledge in natural resource management and decision-making.

Lessons learned

The four breakout groups expressed that they needed time to establish a common understanding of what challenges could be relevant to focus on and especially on how to start constructing the network. One breakout group spent most of the time defining different potential challenges, while the other three spent most of their time constructing a network based on a chosen challenge (see figures below).

The feedback from the participants was that it was challenging to start thinking from a systems perspective. However, once they started, they indicated that the exercise was very useful to understand better the context within which the challenge was set.

Some participants indicated that it is a challenge to get decision-makers and scientists to use their local expertise, pushing them into an opponent/advocacy role rather than being a consulting partner regarding the consequences for the living resources. There was consensus that a systematic approach should be established to connect user knowledge with conventional scientific knowledge to inform decision-making. This was framed as part of the updated "Manaus Letter: Recommendations for the Participatory Monitoring of Biodiversity" sent to the Director of the Secretariat of the Convention on Biological Diversity (see deliverable 2.3).

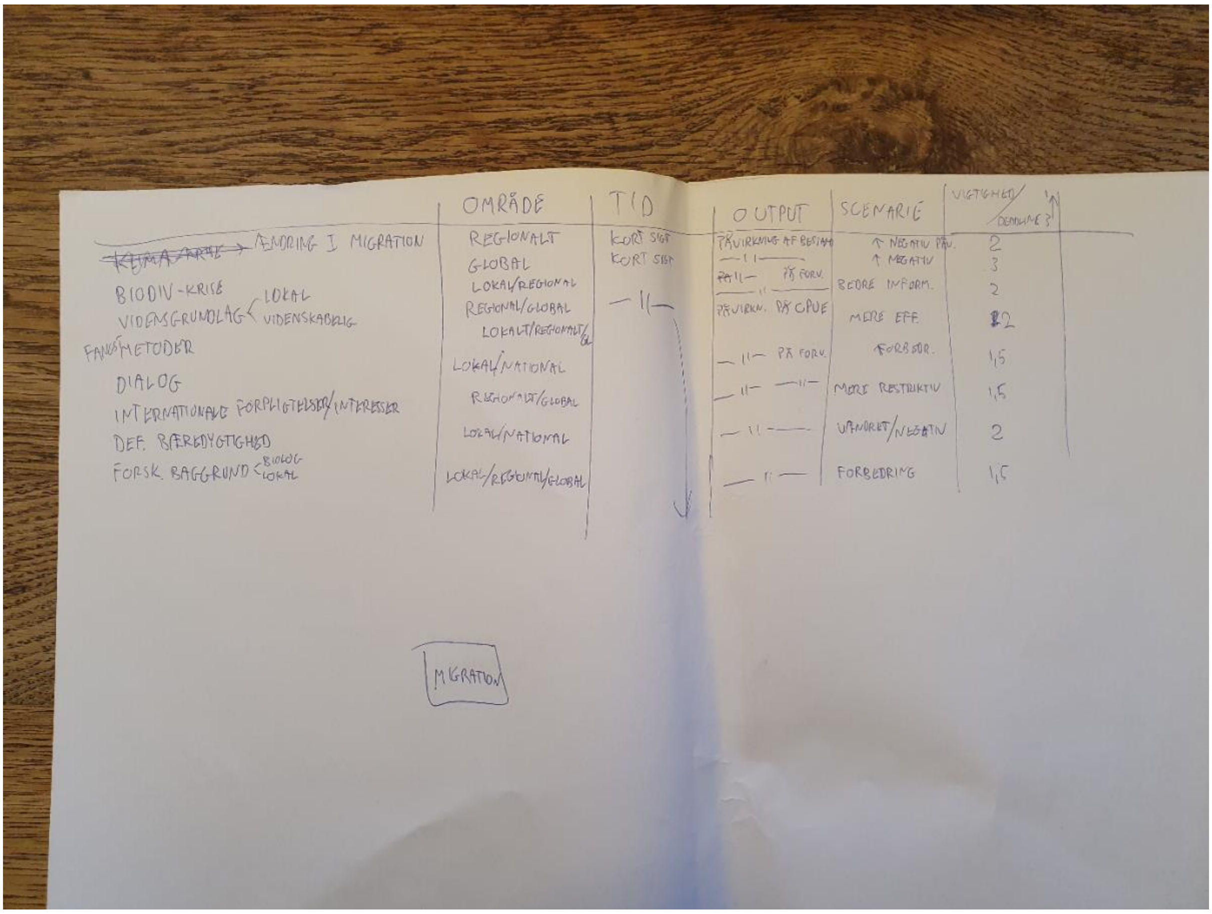


Figure 3. Group work output from the Aasiaat workshop.

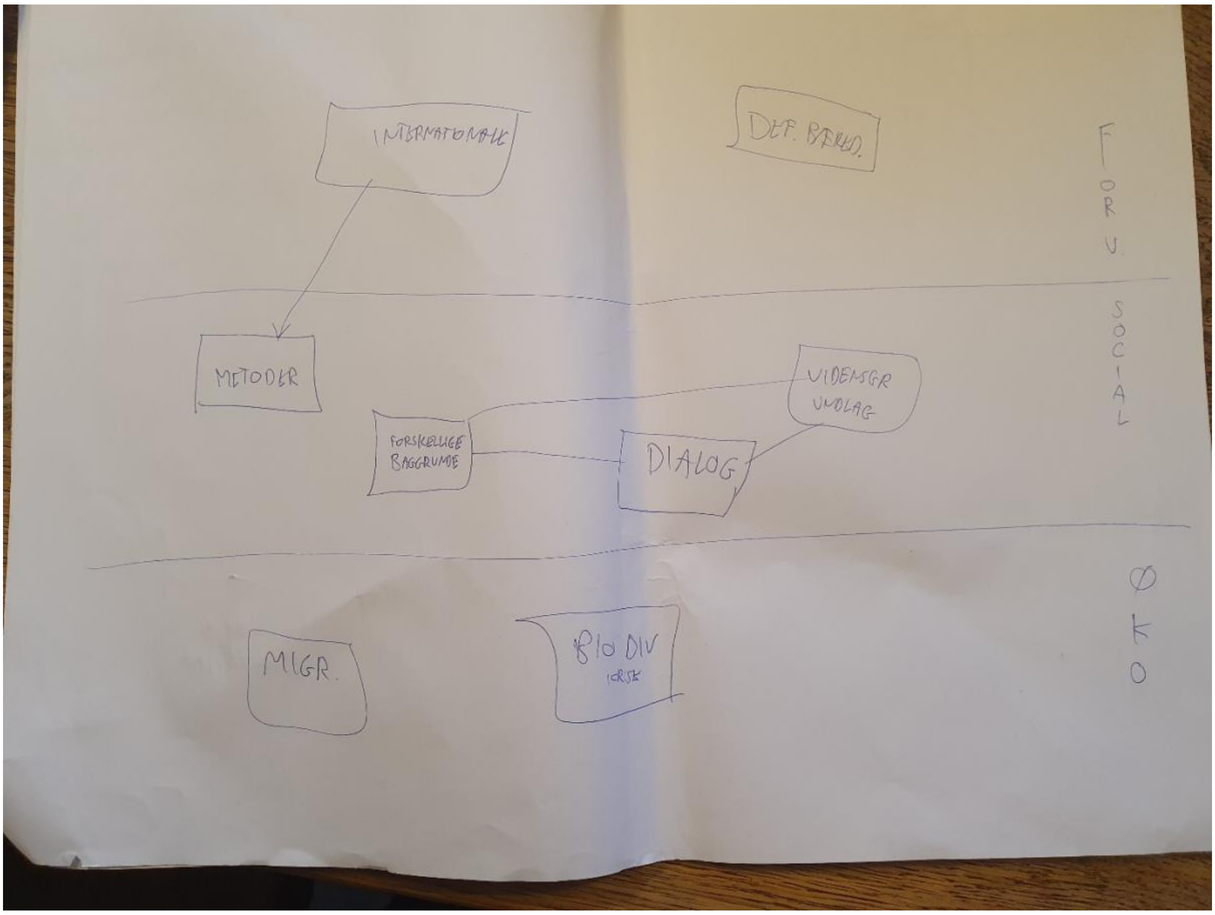


Figure 4. Group work output from the Aasiaat workshop.

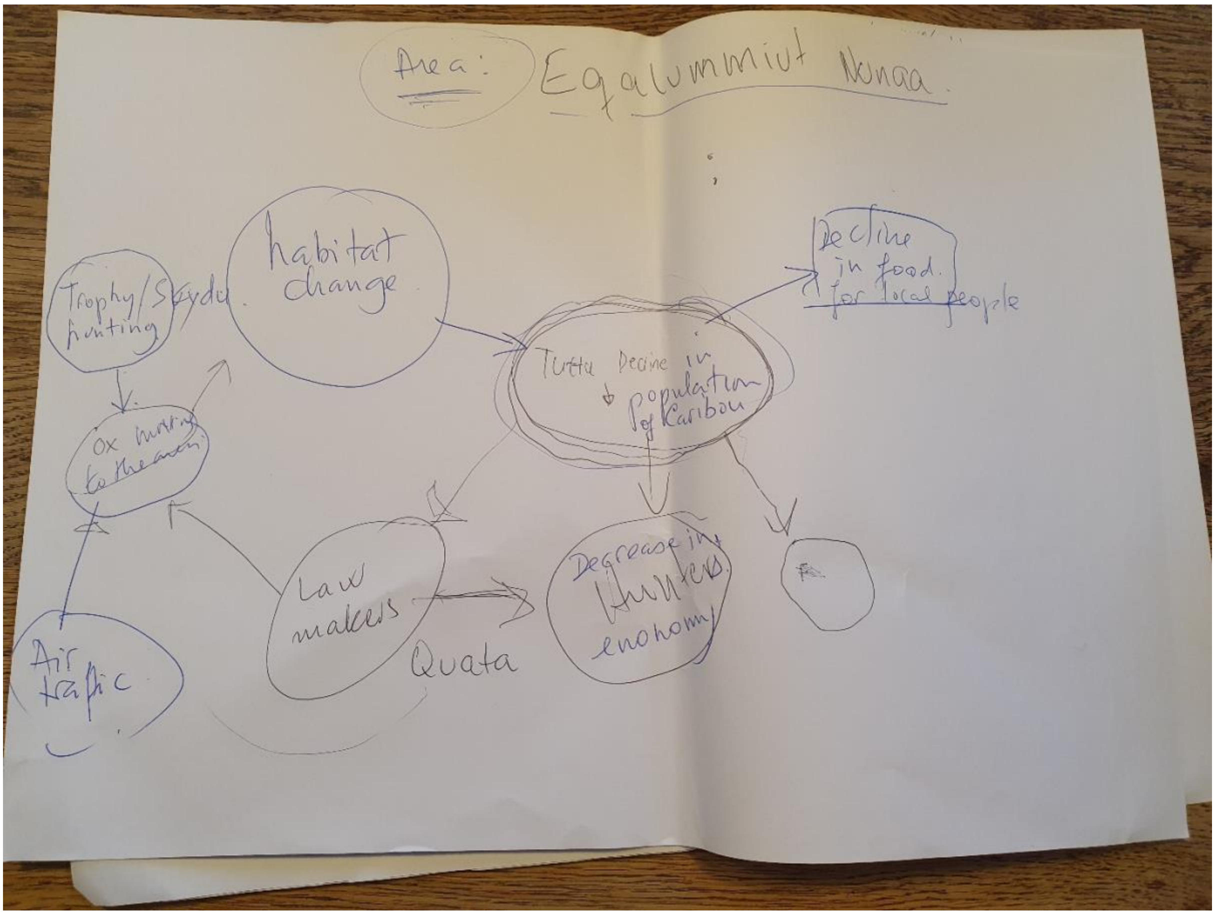


Figure 5. Group work output from the Aasiaat workshop.

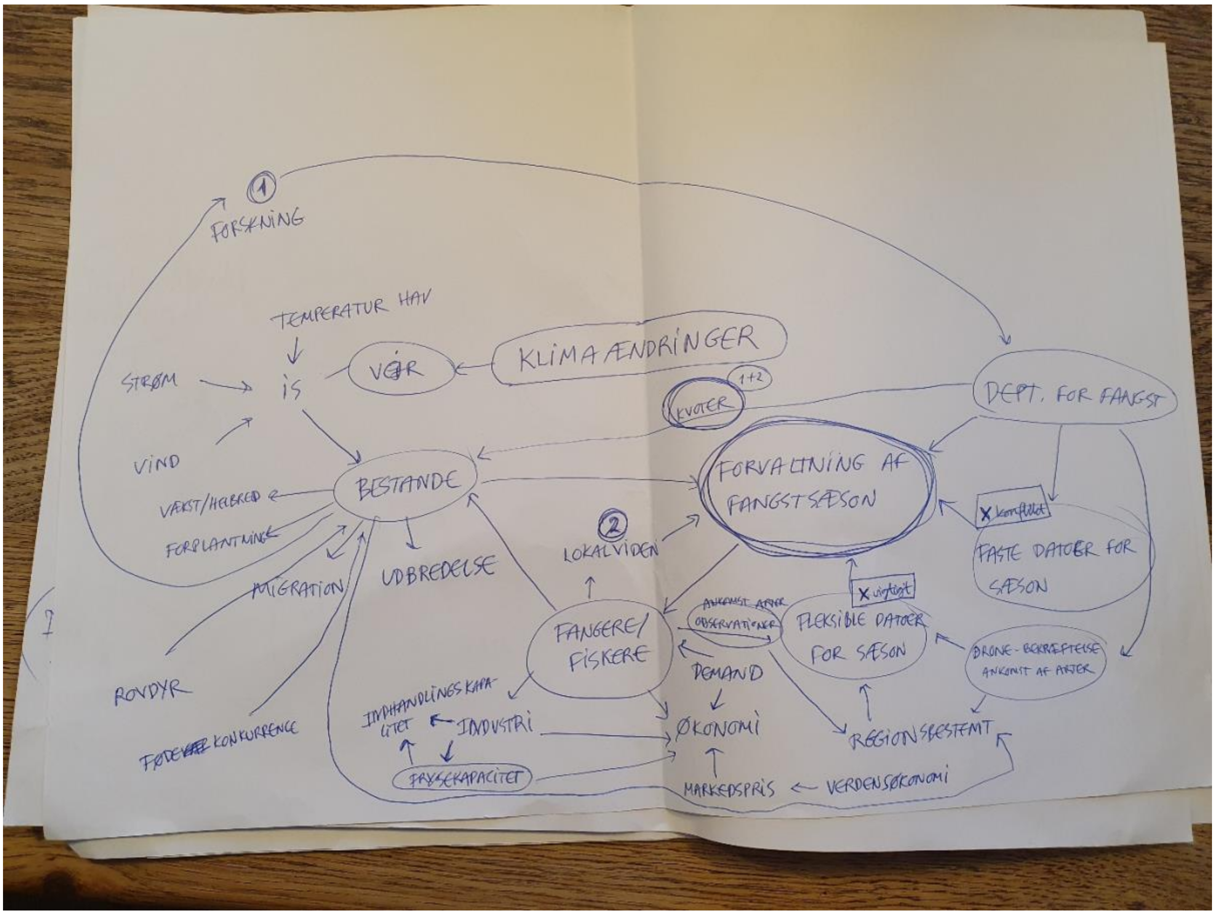


Figure 6. Group work output from the Aasiaat workshop.

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