Department of Sociology, Environmental and Business Economics
Faculty of Business and Social Sciences

Working Paper
No. 3/2019
ISSN 2596-4038

# Growth, Transition, and Decline in Resource Based Socio-Ecological Systems

**Brooks A. Kaiser**

# Growth, Transition, and Decline in Resource Based Socio-Ecological Systems

Brooks A. Kaiser [a,b]

[a]University of Southern Denmark, Niels Bohrs Vej 9-10, 6700 Esbjerg, DK, baka@sam.sdu.dk

[b]University of British Columbia, Institute for the Oceans and Fisheries, AERL, 2202 Main Mall, Vancouver, BC, Canada V6T 1Z4

PLEASE DO NOT CITE WITHOUT PERMISSION.



Editor: Chris Horbel

Department of Sociology, Environmental and Business Economics - SEBE WORKING PAPER 3/2019 - ISSN 2596-4038

SEBE Working Papers are jointly edited by the research groups Management & Economics of Resources & Environment (MERE), Rural and Cultural Sociology, and Markets, Organization and Behavior.

## Abstract

Globalization transforms communities. Increased trade and technology can disrupt existing socio-ecological systems that may have persisted for hundreds or thousands of years. Whole socio-ecological systems may be destroyed or subsumed into a new dominant culture, as has occurred with many Indigenous cultures worldwide. In this context, I examine the Thule Inuit culture as a dynamic and multi-trophic socio-ecological system. Lessons from the study clarify fundamentals of trade and development: mutual benefits from trade rely upon equitable terms that sustain the original stewards of the ecological resource base; the ability to achieve such equitable terms is a function of governance mechanisms and capabilities; and the need for such institutional tools and governance mechanisms should be internally as well as externally recognized for all trading parties.

The multi-trophic model includes three layers: a composite ecosystem resource base, a resource-dependent human population, and a top trophic human group of Traditional Ecological Knowledge (TEK) holders connected through caloric productivity and use. I calibrate the model with what can be known or deduced from the historical record and ecological evidence. I examine how new stressors to the Thule Inuit system, including the foreign commercial whaling and fur trading that brought particularly rapid shifts from the 1820s forward, transformed the system dynamics. Differences in the ways in which the two commercial enterprises evolved across Inuit communities, particularly in terms of net changes in access to calories and new technologies, provide comparative insights into how socio-ecological systems can gain or lose as the introduction of trade and technology can shift relative rates of return amongst ecosystem components.

## Keywords:

Thule Inuit, Traditional Ecological Knowledge (TEK), socio-ecological systems, whaling industry, technological change in socio-ecological systems, dynamics of globalization, ecosystem-based trade, Arctic fox, Arctic economic development, fur trade, bowhead whale, walrus.

# 1. Introduction

The study of resource-based and resource-limited economies presents opportunities to identify how interconnected resource bases and dependent human populations develop over time, and in particular how shifts in the access to trade and technology affect this development (Brander & Taylor, 1998; Fisk & Shand, 1970; Kaiser & Roumasset, 2014). Societies in locations that are remote from global trade and that have natural barriers to transport, including Pacific Islands and the Arctic, evolved in relative isolation from the rest of the world until recent centuries. These locations have unique socio-ecological systems of resource use and governance that have lasted into the recorded historical age (Kaiser & Parchomenko, 2018; Kaiser & Roumasset, 2014; McGhee, 2007; Southcott, 2010).

Thule Inuit, who replaced earlier Arctic cultures while populating the high Arctic between eastern Russia and Greenland beginning in the west around 1000 AD and spreading east over the next 300+ years, are one such socio-ecological system. I model the Thule Inuit societies as a multi-trophic system in which a central human population harvests resources from a composite resource base. In turn, the human population base potentially supports a top trophic class (e.g. elite or specialized Traditional Ecological Knowledge (TEK) holders) that can provide capital accumulation, management and/or governance.

The model can be used to explore how disturbances to the socio-ecological system from increased contact with outside communities and other external factors affect the dynamics of a system. The Inuit system studied here had experienced long run success. Inuit culture thrived in spite of a fragility born from the fact that marine mammal harvest provided the majority of not only caloric intake, but of all other survival materials, including fuel and much clothing. This success rapidly deteriorated with the introduction of trade, new technologies, and disease, all of which are examined through the dynamics of the multi-trophic model.

The case provides a microcosmic view of how broader global contact with socio-ecological systems transforms, absorbs and/or destroys existing systems, as well as of the socio-ecological mechanisms that lead to any system at its limits failing to adjust to changes in the resource base and its productivity. Kaiser and Parchomenko (2018) provides a sketch of the model and presents sparse evidence substantiating stylized facts about past and recent historical Inuit economic development. The outline and structure of the model is illustrated in Appendix A. In this paper, I formalize the model and use it to investigate comparative dynamics based on questions posed by the economic history of Inuit community development.

The two main questions are: how does TEK, as human capital and useful knowledge, influence the resource efficiency and capital deepening and broadening opportunities present in the socio-ecological system, and how do terms of trade affect the system's potential for growth and collapse? The latter question has two aspects to consider: the effect of resource extraction from outside the system, and trade's ability to change the relationship between TEK and the resource base.

The base of the socio-ecological system is a composite resource stock, or ecosystem. Resources are harvested for use by a human population, where the resource stock is subject to natural biophysical limits. As a composite stock, the intensity of ecosystem use will vary as the net benefits for components of the system change. The biophysical constraints of the ecosystem have dynamic feedback effects on its composite stock. The transactions costs of managing and governing harvest from a composite ecosystem affect the dynamics of the constraints; for example, higher transactions costs will lead to lower levels of governance, ceteris paribus. The harvested ecosystem stock can be used for three purposes: consumption by the subsistence-motivated, endogenous laborer portion of the population; export in exchange for goods external to the resource base; and/or capital or wealth accumulation. Capital accumulation can sustain a governing managerial class whose contribution to growth stems primarily from increased returns to capital through the ecosystem dispersion (resource intensity) coefficient. The governing class is considered, in the language of ecology, a 'top predator,' and may be quite small. This 'top predator' can provide capital accumulation and technological change, or may attempt to siphon off wealth to generate consumptive but not dynamic investment benefits. These multi-trophic interconnections differentiate and broaden the story from existing literature on primarily open economies in which resources are providing different returns from physical and/or human capital (Carboni & Russu, 2013; Eliasson & Turnovsky, 2004; Lopez, Anriquez, & Gulati, 2007).

The top trophic level in Inuit Arctic communities should not be considered an elite in the traditional sense of a ruling hierarchical class, but rather as human capital manifested in TEK. TEK can work in either or both of the following ways. First, it can serve as capital deepening, directly increasing the efficacy of resource harvesting, e.g. improved harpooning. This results in directly increasing labor productivity (catchability) and in turn, in increasing harvesting pressure on the resource.

Second, TEK can increase the composite resource's productivity. It does this by e.g. improving use of marine mammal parts for more effective sustenance and survival tools– essentially capital deepening, or developing new benefits from previously unused ecosystem components – essentially capital broadening. Thus, TEK may either increase or decrease resource pressures, depending on how relative growth rates of the resource and the population shift – that is, whether life (wealth) is improving in such a way that, consumed and invested by the human population, expansion or contraction follows[1]. This latter use of capital may allow for reduction in intraspecific competition of the human population, through e.g. territorial expansion into unused resources. Changes in exogenous resource values, governance and transactions costs of enforcing resource use for wealth accumulation, including maintaining an elite or governing class, and/or for trade, including defining property rights, regulating markets or other governance of exchange, are investigated in order to explore the co-evolution of useful knowledge and resource pressures.[2] Useful knowledge here means knowledge of natural phenomena that functions as a source of growth (Mokyr, 2002)

[1] Important exogenous population shifts from contact with new diseases can also be considered in this framework.
[2] Both methods of capital development for subsistence in Greenlandic Arctic conditions were attempted at the beginning of the second millennium AD. The Inuit arrived from the north and west, while Norse settlers arrived from the east. The Norse brought hunting, fishing, agricultural and animal husbandry technologies that had developed in similar Norwegian conditions that facilitated natural capital deepening. The Norse socio-ecological system generated sufficient surplus to support a population of a few thousand humans and top predation by both the Catholic church and the evolving Norwegian state, but only so long as walrus tusk prices remained high and metals, timber and long distance transport ships could be relied upon from outside the Greenlandic resource base (Nedkvitne, 2019). The Norse in Greenland, as a subset of the greater North Atlantic medieval socio-ecological system, provide an interesting comparative system to investigate in future work.

## 2. Inuit societies as a model case

Inuit societies spanning from the Bering Sea (modern day Alaska) to Davis Strait (modern day Canada)[3] define and motivate a case where limits on the composite resource base reduced the advantages and opportunities for capital accumulation. The development of a managerial capital elite was minimal, consisting mostly of human capital in the form of specialized TEK (Betts & Friesen, 2004; Friesen, 1999). Thus, the top trophic layer in the socio-ecological system simplifies for clear focus on human capital and useful knowledge.

Prior to the introduction of external trade, growth remained primarily extensive through eastern expansion across the Arctic region, above the tree line (Raghavan et al., 2014). TEK that was specialized on marine mammal and tundra ecosystems was productive (Betts & Friesen, 2004; Freeman et al., 1998; Nuttall, 2005); large marine mammal harvest required small group coordination, but without significant asset storage, wealth accumulation and physical capital investments were minimal. Resource harvest was costly, and with the availability of extensive growth across the Arctic marine tundra (Anderson, 2011; Aporta, 2009; Betts, 2007), the harvest generated neither the significant booms nor dramatic collapses that have been witnessed in some isolated communities like Easter Island (Brander & Taylor, 1998; Diamond, 2005).

Inuit Arctic food chains are short in length, and the composite resource base is well-illustrated in Figure 1. Missing from the food chain, and yet an important ecosystem component for Inuit economic development, is the Arctic fox. This distinction of the fox as part of the ecosystem resource base but not the food chain provides an unusually clean delineation between growth from useful knowledge and growth (or decline) from trade.

[insert figure 1 about here]

---

[3] Inuit society extends west into and throughout Greenland. The modern Greenlandic story, however, which begins with the exploitation of the Spitsbergen fishery begun by the Dutch in the 1600s and continues to the present, is mainly set aside for future consideration. This is in part due to the poorer quality of 17th and 18th century data, during which these bowhead whale stocks were almost completely depleted (Allen & Keay, 2006) and in part due to the direct and extensive intervention of the Danish government into Greenlandic economic and social development (Hamilton & Rasmussen, 2010; Tejsen, 1977).

The introduction of trade and new technologies initiated dramatic shifts in the returns to different components of the resource base, particularly between marine mammals and Arctic fox, as well as to the labor harvesting it (Bailey, 1993; Bockstoce, 2009; Damas, 2002; McGhee, 2007). These shifts are discussed in the context of the model to highlight the differences in effects on the socio-ecological system dynamics. In so doing, the options that the socio-ecological system might face in balancing the impacts from change include governance responses, resource depletion, system exit, and capital deepening and/or broadening. In the case of Inuit socio-ecological systems, the lack of a strong managerial elite combined with changing terms of trade for components of the composite resource base to drive a shift in TEK's role as useful knowledge and to impact the social structures more broadly.

The multi-trophic structure and the inclusion of governance and other institutional costs render the model very rich in potential detail. This requires some executive decisions regarding the direction of focus. Thus, I limit the focus to questions surrounding the introduction of trade and the changing roles of TEK as a resource capital deepening and broadening technology, to which the Inuit case can provide particular evidence.

The pertinent historical period for Inuit societies divides into three potentially overlapping states related to the introduction of trade: (1) 'pre-trade', (2) 'resource extraction without compensation', and (3), 'mutually beneficial trade'.

## 2.1 Pre-trade

Archaeological and anthropological evidence pertaining to the stable, slow growth of the human trophic layers of Thule Inuit societies before significant external trade (Anderson, 2011; Aporta, 2009; Betts, 2007; Raghavan et al., 2014; Rasic, 2016) is used to parameterize the pre-trade state. The evidence establishes the socio-ecological system as one of small communities experiencing external growth through eastern migration from the Bering Sea. In this era, TEK is strongly developed, but not all of the ecosystem's components are productive for the human trophic layers in the system; of particular relevance for this analysis, Arctic fox is left unharvested. Specialized TEK used in coordinating large marine mammal harvest (through e.g. whaling captains) results in a distribution of returns across human trophic layers to facilitate the shared harvest tasks. Figure 2 illustrates the potential divisions of a whale, with Table 1 providing additional details on how present day communities share the harvest based on cooperative inputs.

## 2.2 Resource extraction without compensation

Commercial whaling and walrusing by agents outside the socio-ecological system, particularly the Northern European and North American whaling fleets of the 17th-19th centuries, reduced the Inuit resource base without meaningful payment to Inuit societies. The actions and effects of these withdrawals from the resource base characterize the second state, which is dominated by ecosystem depletion and subsequent decline in the resource-dependent Inuit populations. Significant whale extraction levels start in the Eastern Canadian Arctic after 1819, followed by walrusing a few decades later (Coltrain, 2009; Coltrain, Hayes, & O'Rourke, 2004; J. Higdon, 2008; JW Higdon & Ferguson, 2010; Stewart, Higdon, Reeves, & Stewart, 2014). Commercial whaling in the Western Arctic, north of the Bering Strait, started in 1848 and continued through the century (Bockstoce, 1986). In Figure 3. Spatial sample of American Commercial Whaling Strikes in the Pacific Arctic, 1844-1912 (AOWV database)Figure 3, whale strikes from a subset of whaling voyages for which I have explicit spatial data show the concentration of whaling in the western Arctic, and its spread over time further eastward along the Canadian coast.[4] There are 163 voyages with spatial data that caught bowhead whales shown here, from over 16,000 known American whaling voyages; the map significantly underrepresents the presence of the American whaling fleet. Table 6 and Table 7, discussed below, show summarized totals.

[Insert Figure 3 about here]

In both east and west, the deleterious effects of whaling and walrusing were directly evident to the commercial whalers and Inuit alike at least by the 1870s, but industrial and social conditions were such

[4] The complete dataset consists of daily logbook data from 1,381 logbooks from 1784-1920, from approximately 16,000 whaling voyages documented in the American Offshore Whaling Voyage Database (Lund, Josephson, Reeves, & Smith). Logbook data north of 47° begins in 1844 and ends in 1912.

that the tragedy of the commons problems could not be resolved. Some captains called directly to the American fleet to cease walrusing in the west in order to protect Inuit populations.[5] Other captains answered in plain language, with reference to the self-interested incentives that drive the standard commons problem: ‘if I don’t take the walrus, another will.’ (Bockstoce, 1986; Hardin, 1968). In the east, it was not until 1928 that walrusing ceased, due to a commercial ban by the Canadian government implemented in an attempt to reverse the damages.

## 2.3 Mutually beneficial trade

Inuit in Southern Labrador experienced some of the earliest sustained Inuit trade opportunities through a Moravian missionary established in 1771. The anthropological and archaeological literature supports the hypothesis that once Inuit contact with Europeans became trade based, the Inuit communities shifted their relationships to the ecosystem in favor of production of tradable goods (e.g. seal boots, seal oil, cod) but that this did not, on its own, instigate broader structural changes in Inuit culture or institutions (Brewster, 2005; Cabak & Loring, 2000). It may, however, have changed hierarchical dynamics within Inuit communities as some Inuit sought greater returns through organizing and managing trade (Arendt, 2010; Brewster, 2005); these shifts had little potential to spread through Inuit communities as later trade posts remained primarily in military or company control (Arendt, 2010).

Fur trading, especially for Arctic fox, illustrates the third state more broadly (Bailey, 1993; Barr, 1994; Bockstoce, 2009; Dalen et al., 2005; Gagnon & Berteaux, 2009). Foxes, as small scavengers that can feed on carrion, are neither a preferred nor significant component of the human diet (Wein, Freeman, & Makus, 1996). As such, they had little role in sustaining the upper trophic levels of the Inuit system before the introduction of trade. Trade for fox furs shifted returns to ecosystem harvesting and TEK from marine mammal harvesting to fox trapping. This shifted the need away from coordinated hunting and reduced the value of an Inuit whaling-captain’s leadership in the community, as well as his ability to draw benefits from it. The introduction of goods that further reduced the dependence on TEK created opportunities for exit (besides death) from the socio-ecological system to other forms of livelihood.

[5] A particularly poignant letter calling for an end to walrusing from Frederick Barker in 1871 after he and his crew were saved by Inuit over the course fo a winter stranding was published in several New Bedford newspapers and the Whaleman’s Shipping List, as recounted in Bockstoce, 1986.

Whether this was a welfare increasing opportunity or welfare decreasing necessity is crucial to understanding the larger question of the net gains to trade. The information available, included what the right measure of welfare would be to capture the tradeoff adequately, does not allow a clear answer here, where the focus is instead on the viability and success of the socio-ecological system as an alternative state to one where trade and resource commodification acts to integrate values and opportunities into more homogeneous regional or global systems.[6]

# 3. Model

## 3.1 Existing literature and model aims

Economic theory has benefitted from the study of isolated socio-ecological systems when attempting to disentangle effects of extensive and intensive growth, trade, technology and institutions in more complex globally integrated economies. Many such models, however, take resource development to be monotonically linked to population dynamics (e.g. Brander and Taylor, 1998). While a useful simplification in many cases, this does not facilitate exploration of dynamic factors in resource use that are not tied to local populations: new trade opportunities and introductions of species and/or disease, technological progress, or development of a capital-intensive class. The centuries-long, ongoing integration of Inuit economies and societies into the high-GDP economies of the US and Canada provides opportunity to investigate the more nuanced dynamic relationships between a resource base and the humans exploiting it, including governance and institutional structures.

Kaiser and Roumasset's (2014) multi-trophic model of Hawaiian long run development weaves two strands of economic theory together: New Institutional Economics, to address costs and benefits of governance, trade, and institutional and technological change (see e.g. Ménard and Shirley (2005)), and Resource and Ecological Economics, to expand upon ecological models of resource dependency (see e.g.

[6] Inuit in Southern Labrador experienced some of the earliest sustained trade opportunities through a Moravian missionary established in 1771. The anthropological and archaeological literature supports the hypothesis that once Inuit contact with Europeans became trade based, the Inuit communities shifted their relationships to the ecosystem in favor of production of tradable goods (e.g. seal boots, seal oil, cod) but that this did not on its own instigate broader structural changes in Inuit culture or institutions (Arendt, 2010; Brewster, 2005; Cabak & Loring, 2000). It may, however, have changed hierarchical dynamics within Inuit communities as some Inuit sought greater returns through organizing and managing trade (Brewster, 2005); these shifts became less prominent as later trade posts remained primarily in military or company control (Arendt, 2010).

Costanza et al. (2014); Costanza, Wainger, Folke, and Mäler (1993); Eide and Flaaten (1998); Rodseth (2012); Van den Bergh (2002)). In the case of Hawaii, gains from specialization and the development of a productive managerial elite evolved to the point of an Archaic state before contact with outside influence (Kirch & Sharp, 2005). British naval exploration at the end of the 18th Century disrupted returns to capital and trade and, in adapting to new terms of trade and returns to management, capital investments and technologies, it changed the path of institutional evolution (Kaiser and Roumasset, 2014). This model's flexibility and richness is adapted for the Inuit case.

While the Inuit and Hawaiian cases are both historically isolated communities dependent on a limited supply of natural resources and technologies, distinctions between the two communities hold particular significance in long run development, especially with respect to the building, use and management of capital. The multi-trophic model used here is able to distinguish these nuances. By bringing anthropological and other scientific research to bear in the economic model (e.g. (McGhee, 2007; Raghavan et al., 2014), I separate and examine trade and technological evolution as they interact with the Arctic marine and tundra resource base and human population over time.

## 3.2 The multi-trophic system

I introduce the components and vocabulary of the model, summarized in Tables 2-4, in order to simplify exposition of the dynamic system and optimization problem. The optimization problem is to maximize social welfare derived from harvesting the resource base. The social welfare can come from any of three activities: direct consumption of the base (subsistence), direct consumption of the base that feeds TEK holders (human capital investment in useful knowledge), or value derived in trade (in goods external to the socio-ecological system).

## 3.3 Societal overview

Society strives to maximize the value derivable from its composite resource base, both today and into the future. It does this through harvest. Catchability can be divided into a knowledge component – what is known through TEK about the ecosystem's productivity, and a governable technological component – the application of knowledge and capital to what can be feasibly caught. Catchability is then measured as the product of the technological coefficient and the TEK-dependent resource intensity coefficient, discussed further below. The two interact to determine the laboring population's harvest from the resource base at any given time.

I model this optimization process with a dynamic optimal control multi-trophic predator-prey model. Society maximizes economic value (total net benefits), over time, through costly decisions regarding the shares of the resource to non-laborer consumption. These consist of the share of the resource to trade and the share of the resource (through labor) to TEK capital accumulation. The remaining share of the resource goes to laborer consumption.

[Insert Table 2 about here]

### 3.4 Value of the resource over time

The value of the resource to society derives from its division: I assume the share to immediate consumption is worth $V_t$ per unit of well-being today, and that it provides the base for human population growth for tomorrow.[7] The share to trade is exported for per-unit current benefit acquired in trade and can enhance or detract from future growth in the capital (elite) or commoner population depending on the goods purchased and the equitability of the terms of trade. The share to the elite (TEK capital) creates value through investment in the human capital (TEK) of the population, which works endogenously to increase capacity by increasing knowledge needed for resource use intensification. The sum total determines the remaining resource base available for growth (or replenishment) and future value.

#### 3.4.1 Value from laborer consumption

In addition to the current benefits of consumption, the current harvest affects the future resource base and human commoner population. In the model, the resource base grows according to a standard logistic

[7] For other applications in which e.g. intra-trophic and/or intra-societal trades are more intriguing, the marginal value of consumption of the resource for human subsistence by commoners/laborers can be more generally generally represented as a decreasing benefit (utility) function. In this case, where such a function would be mainly arbitrary, I simplify to an exogenous per unit benefit value, $V_t$.

growth function net of harvest. The human laborer population tomorrow is a function of the ability to convert consumption to growth (via an intrinsic growth rate), the death rate of the population, and the intraspecific rate of competition, i.e. the rate at which members of the laborer population compete for the same resources. If there is no deadly competition for the resource base, then this rate is zero. This implies that the population can expand with extensive growth (e.g. into new resource-sufficient areas). For the purposes here, this matches the historical record and is assumed to be the case. The death rate could similarly be modeled as an explicit function of levels of TEK or export price, but for simplicity in this case, it varies only exogenously over time, primarily to capture the impact of disease introductions.

### 3.4.2 Value from Human Capital formation

The marginal benefit (utility) of capital accumulation may be described generally as a decreasing benefit function where total benefit from TEK (capital) is the integral of this function over the level of capital. Here, I simplify to an exogenous value, $V_{kt}$, that can be shifted by changes in the benefits of wealth (perhaps prestige, power, or access to luxury goods). The share to capital contributes to current well-being through a technical transformation from the resource into capital. Investment can generate new capital formation by adding to the number of TEK holders, but more slowly than the laborer population can grow.

The opportunity costs of TEK are the reduction in resource availability for trade or commoner consumption (and direct laborer population growth). Capital investment or exogenous shifts in technology change the rate of this transformation from resource to capital. I assume that investment and/or contact with others through trade could increase the ability to transform the resource into capital value and would thus increase the amount of capital available to the system. TEK depreciates; one may consider the rate at which this happens as equal to the mortality rate for the holders of TEK.

### 3.4.3 Value from trade

The marginal benefit (utility) of the resource as an export commodity is represented by a downward sloping demand function. I simplify this to an exogenous price, $P_t$, that can be shifted by changes in opportunities for trade. The current net benefits to trade must be balanced against the lack of availability of that resource for either consumption or capital purposes so that human laborer population and capital growth will be lower with more trade, unless trade replaces the lost resource base with new opportunities. These may include direct food supplies or changes in technology that affect the potential catchability. Control of the resource for trade and the distribution of returns from trade are then important factors in support for the institutional structure of the economy.

[Insert Table 3 about here]

## 3.5 Costs

The benefits of the harvest are countered by the costs of the harvest and costs of harvest governance[8], which apply regardless of end use of the resource. Here I discuss the relationships between marginal costs and the working of the resource dependent system. Note that all of these costs may also change through exogenous shocks over time.

### 3.5.1 Current Harvest Costs and Costs of dispersion

The per-unit cost of harvest may be a function of the resource population and/or capital stock, but it is modeled here as exogenous for simplicity. The effects of changes in the per unit enforcement costs of the shares to capital accumulation and trade (described below), are expected to behave very similarly, and the sensitivity of the catchability coefficient to capital stock can be expected to act in the same manner as decreasing costs from increases in the stock (and vice-versa). Furthermore, the dynamics of endogenous harvest costs are well explored in the fisheries literature (Squires & Vestergaard, 2013).

Economics generally proposes that failure to limit the harvest today results in overharvesting and inefficient allocation of the resource base across time (Hardin, 1968). This will not be the case, however, if resource pressure is sufficiently low that open access does not jeopardize the future harvest. The possibility of illicit harvesting within the Inuit socio-ecological system is also low in the case of large marine mammal harvests, as harvesting relies on collective action and specialized human capital. On the other hand, the effects of harvest from outside the socio-ecological system may be so abstractly related

[8] Recall the costs operate through costs of TEK-influenced dispersion rather than direct harvest restriction in this case.

to existing governance and knowledge systems that no effort or expenditure can be or is made on monitoring or enforcement.

An example of this might be as follows. A community is harvesting seals with essentially constant returns to scale and has no need for limits due to high abundance of seals and low human population. Arctic fox are not harvested – dispersion in ecosystem use is relatively low. Trade arises; fox fur becomes valuable for trade. TEK may be developed to also trap fox (TEK increases through increased share of the resource base) – in turn the use of the ecosystem becomes more broadly dispersed, and costs of this ecosystem harvesting as a whole are now higher. There is no concurrent development in governance institutions, however, as harvesting fox does not require collective action, and community investments used for trade (e.g. trading posts, ports) were made by outside agents.

### 3.5.2 Current Enforcement Costs of Non-consumption

In theory, the costs of enforcing the division of the resource base can be used to illustrate how shifts in external prices for the resource base may create different pressures and costs on enforcement and to reflect better on the role of management and human capital. The costs of portioning off the share to TEK holders, or capital accumulation, are non-decreasing in the share to capital. This is because the more of the resource that is taken from laborer consumption, the greater the monitoring costs and related costs of ensuring that the capital is efficiently allocated.

The costs of governing the share to TEK holders are also non-decreasing in the number of people needing to cooperate, as one expects in commons problems. For simplicity, costs of enforcing a share to trade are assumed to be linear in the share to trade[9]. Costs of enforcing a share to trade are modeled as non-decreasing with population levels. This is because the opportunity cost of trade over consumption will increase and/or more individuals involved in trade will result in more parties to monitor who might rather consume the resource.

---

[9] They could instead be modeled as increasing for the same reasons as drive the assumption that costs of governing the share to capital are increasing in the share of capital, $\frac{\partial w_{\varphi}}{\partial \varphi} \geq 0$.

[Insert Table 4 about here]

### 3.6 Resource Harvest

The composite resource is harvested by the population at a per capita rate, $c \cdot \gamma(K_2)$. This rate is similar to a standard bio-economic catchability coefficient (*q*), or in other words the ability of the population to acquire the resource for sustenance, but more explicitly combines capital broadening possibilities with potential governance. It is thus divided into two components, a direct control variable, *c*, and an indirect control through TEK investment, $\gamma(K_2)$. That is, in addition to its potential for direct control, the range of the coefficient may be a function of TEK (human capital). With respect to the latter characteristic, increases in capital investment (and/or harvest technology) increase catchability of the resource base. The more abundant the resource, the easier is the harvest, ceteris paribus.

Catchability is a function of the resource intensity coefficient $\gamma(K_2)$, reflecting the transfer of TEK to catchability. This transfer is such that increasing TEK increases the usability of the composite resource – in other words the resource intensity coefficient reflects breadth of use. Thus, it can also be considered a dispersion coefficient that captures how much of the composite ecosystem base can be harvested and used. If TEK fails in the extreme to enable any transformation of the ecosystem base into sustenance, for example all hunting techniques are ineffective, then no harvest is possible, as no component of the composite resource can be made valuable. If TEK is fully implementable for the environmental conditions, then the population has full use of the ecosystem and uses maximum catchability for the existing technology. The intensity of harvest can then increase through capital deepening or decreased, if necessary, through governance mechanisms over the catchability.

Whether or not this maximum rate is sustainable cannot be fully addressed without application of governance. The lack of institutional mechanisms governing harvest rates in Inuit societies testifies to the fact that this potential governance control was not much developed or utilized. For this reason, I treat the non-TEK component of the catchability coefficient, *c*, as an unutilized control that may yet be affected by exogenous shifts in e.g. technology. This highlights one of the long run failings for adjustment in the socio-ecological system; without use of the control as resource stocks dwindled due to external forces, the full impact of the reduction must be felt in the remaining dynamic forces.

With respect to the component of catchability that is determined by TEK holdings, I assume that the resource intensity coefficient is increasing at a decreasing rate in TEK investment. Achieving the useful knowledge to fully develop the maximum catchability rate may depend on coordination activities by the TEK holders, as with whaling operations. It is mainly in this dimension that TEK led to development of leadership and governance.

## 3.7 The optimization model

The maximization problem aims to maximize the value generated from the ecosystem for its Inuit stewards, and can be written as:

$$Max\int_{t=0}^{\infty} e^{-rt}\left( V_{kt}K_{2t} + \begin{pmatrix} P_t s_t - w_{st}(\mathrm{N})s_t \\ +(1-s_t)(1-\varphi_t)V_t - w_{ct} - w_{\gamma t}\gamma(K_{2t}) \\ -w_{\varphi t}(\varphi_t,\mathrm{N})\varphi_t \end{pmatrix} \gamma(K_{2t})c_t R_t N_t \right) dt \qquad 1.1$$

subject to equations of motion for the resource and laborer populations and the evolution of the elite (TEK capital stock) as shown here. Note that in the remaining text, the time subscript is suppressed.

The equation of motion for the resource is:

$$\dot{R} = \underbrace{g_R R\left(1-\frac{R}{K_1}\right)}_{natural\ growth} - \underbrace{\left(\gamma(K_2)cR\right)N}_{human-population\ dependent\ harvest} \qquad 1.2$$

The resource population $R$ follows a logistic growth function with a human population-dependent harvest. Here $g_R$ is the intrinsic growth rate of the resource and $K_1$, the carrying capacity at $t$ of the resource.

The equation of motion for the human laborer (commoner) population is:

$$\dot{N} = N\left(\underbrace{g_N\left(1-\varphi\right)\left(\gamma\left(K_2\right)cR\left(1-s\right)\right)}_{resource\ dependent\ natural\ growth} - \underbrace{d}_{death\ rate} - \underbrace{\chi N}_{intraspecific\ competition\ \text{or}\ cooperation}\right) \qquad 1.3$$

where $g_N$ is the intrinsic growth rate (conversion efficiency) of the human laborer population and $d$ = death rate of laboring humans. $\chi$ is the intraspecific cooperation/competition coefficient at t.[10]

Finally, the equation of motion for knowledge capital accumulation or support of elite TEK-holders is:

$$\dot{K}_2 = \underbrace{A^{\xi}\varphi\left(\gamma\left(K_2\right)cR\left(1-s\right)\right)N}_{investment\ rate} K_2 - \underbrace{\delta K_2}_{depreciation} \qquad 1.4$$

Where $A$ is the technology coefficient at t, along with the growth parameter $\xi$, and $\delta$ is the (exogenous) depreciation rate of capital (e.g. mortality rate for the TEK holders). These technology parameters are summarized in Table 5.

[Table 4 about here]

I generate a current value Hamiltonian using $\lambda, \nu,\ and\ \vartheta$ as the co-state variables for the equations of motion for the resource, human population, and knowledge capital respectively and take the subsequent relevant first order conditions to generate the necessary conditions for dynamic optimization to be as written in Appendix C.

From the FOCs, the co-state variables can be expressed as:

$$\lambda = w_{\varphi}\varphi + w_c + w_{\gamma}\gamma - \left(P - w_s\right) \qquad 1.5$$

[10] I assume for simplicity for the Inuit case that $\chi = 0$, which implies the laborer population can expand with extensive growth. But note that $\chi < 0$ is considered analogous to having economies of scale in population growth that benefits from increased labor, e.g. having sufficient population to use larger boats to acquire larger marine mammals, and $\chi > 0$ implies crowding that requires migration or deaths. The coefficient may also vary with TEK capital, where the assumption that $\frac{\partial \chi}{\partial K_2} \leq 0$ implies TEK capital accumulation can counteract crowding or enhance cooperation by resource-increasing investment, leading migration, and an expanding production possibilities frontier.

$$\nu = \frac{1}{g_2}\left(\left(V - \left(P - w_s\right)\right) + \frac{\varphi}{(1-s)}\left(w_\varphi + \varphi \frac{\partial w_\varphi}{\partial \varphi}\right)\right) \qquad 1.6$$

And

$$\vartheta = \frac{-\left(\left(P - w_s\right)(1-s) + (1-\varphi)\left(w_\varphi + \varphi \frac{\partial w_\varphi}{\partial \varphi}\right)\right)}{(1-s)A^{\xi}K_2} \qquad 1.7$$

Eqn 1.5 indicates that the shadow value of the resource is a function of the full marginal costs of acquiring that unit of the resource, including harvest costs, costs from capital broadening through dispersive use of the system, and costs of capital deepening through TEK investment, net of its value from trade. That is, if trade can replace ecosystem value with external value P, this reduces the scarcity rents on the resource; trade can be beneficial if and only if it outweighs the costs to the system.

From Eqns 1.6 and 1.7 one sees that the shadow values of the human population and capital are functions of the ability to transform the resource harvest into population and capital growth, respectively, including the full costs of governance. Increasing value of the resource base, *V*, increases the scarcity rent on the human population, as one should expect, so does increasing the share to capital; these rents can be compensated if there are net gains in trade. Net gains from trade can increase the scarcity rents on TEK; there is increasing value in the resource base.

Using these equations and their time derivatives with (appendix) equations A.4-A.9, one can solve for a set of intertwined resource paths over time as functions of the many shifting parameters in order to address the sustainability of the system as globalization introduces impacts in the form of resource base depletion, upper trophic population loss from disease, technological shifts from introduced goods and knowledge, and shifts in the ability of the ecosystem to generate economic value. Functional forms of these paths are shown in Appendix C (equations A.10-A.12).

## 4. Application and discussion

I draw on a variety of primary and secondary sources to parameterize each period. In the application, the model is further simplified by focusing on marine mammals as the major sources of calories that Inuit traditionally harvested.[11,12] In the long history of debate on the co-incidence of Norse colonists and Greenlandic Inuit with opposing fates in the first half of the 2nd millennium, the most recent addition to the debate argues that Inuit expansion in small hunting groups (extensive growth from the west) brought the two groups into violent conflict, with the result that the Norse colonies ceased to exist (Nedkvitne, 2019). In the process of the argument, Nedkvitne (2019) establishes convincing evidence of population control among the Inuit based on resource availability and TEK capacity.[13] In conjunction with genetic research regarding population figures for Inuit (Marchani, Rogers, & O'Rourke, 2007), I make an informed assumption that Inuit communities, numbering up to 1500 across the US and Canada, had an effective population of ~100 individuals each, of which ~3 were specialized TEK holders (Associates, 2018). These numbers provide a basis for calibration of the system dynamics.

### 4.1 Pre-trade:

I estimate the total stock of the composite resource base consists of approximately $2.41*10^{13}$ calories of biomass, or the equivalent of about 18.8-21.3 million person-years given caloric needs of 3100-3500 per day (LeBlanc, 1996).[14] Food sources in the calculations include bowhead whales, walrus, four types of

---

[11] Caribou are formally excluded, though they are important for at least some Inuit communities, especially inland and closer to the tree-line, and directly affected by technological introductions, particularly hunting rifles. Caribou meat would at times be a vital component of Inuit diet, but caribou populations suffered their own complex and cyclical resource dynamics that made them less reliable components of the ecosystem (Burch, 2012). Their main contributions may have been more through provisions of clothing and related materials. I consider the exclusion covered sufficiently by the sensitivity analysis of the resource base.

[12] Within this subset, I further exclude polar bears from the analysis. Though an occasional source of food, and presently a seasonal source of cash, seals are more numerous, preferred for taste, and more easily caught, and so have played a much more consistent and significant role in the diet (Wein et al., 1996; Wenzel, 2009).

[13] This challenges the assumption that the intraspecific coefficient $\chi(N) = 0$ in the short run. Without any ability to further quantify the relationship, however, I subsume it into the exogenous death rate of the population.

[14] The caloric needs are higher than most contemporary dietary needs due primarily to more exposure to colder temperatures. Though high, I consider the values more likely to be underestimates than overestimates of the caloric demands on the resource base because dogs have not been explicitly included in the model. Dogs consumed a marine mammal diet and produced energy for transportation at very high metabolic rates (Gerth, Redman, Speakman, Jackshon, & Starck, 2010), and were rarely if ever a source of protein themselves due to their high value for transportation; they could be

seals, generic fisheries (primarily Arctic char), and Arctic fox. Details of these calculations are included in Appendix D.

Table 6 and Table 7 present summary characteristics of the populations and the harvests for Bowhead whales and walrus respectively. These figures are used in conjunction with the information in Appendix D to determine and calibrate a general growth function for the composite resource base.

[Insert tables 6 and 7 about here]

In the pre-trade era, the model simplifies considerably as trade parameters are not relevant. I further simplify for clarity by assuming harvest costs and the cost of enforcing the share to TEK holders are constant.

Finally, with no trade and virtually no ability to store wealth, the system's growth dynamics describe simultaneously what is possible for human subsistence and what is preferred in the system, with the potential exception for differences in contemporaneous gratification between the value of the resource to the laborer population and the value to the TEK holders, which I set aside as unlikely. I thus focus here on the system dynamics as sufficiently informative for the development choices in this period.

The overall direct and indirect effects on the optimal population of the base from resource capital deepening and broadening are ambiguous in large part because humans can internally intervene in the dynamics. At the same time, standard relationships to interior solutions in predator-prey models such as presented in the literature (Clark, 2005); May, Beddington, Clark, Holt, and Laws (1979) are evident. One significant component of the value added here is in the application to the Inuit case, in which the multiple dimensions for human impact on the system can be in large part separated and explored in connection with the historical and scientific records.

Note that the dynamics in this system are driven by choices about the resource use intensity, which changes with TEK. Investments in TEK could change the optimal resource base population; in particular, I define the intensity of use as a function of human capital that ranges from an initial level of useful

---

considered a subset of the laborer population but the complications of estimating the dog population and its specific caloric demands are not necessary for the analysis.

knowledge, $\gamma_0$, which enables sufficient survival skills to maintain a human population from the composite ecosystem resource base, and 1, representing full useful knowledge of the ecosystem, as $\gamma(K_2) = \gamma_0 + \left( \frac{1-\gamma_0}{1+e^{-\beta K_2}} \right)$. If this resource intensity coefficient increases over time, then the optimal resource base decreases, but so will the dependent human population. Being able to draw down the ecosystem does not automatically trigger either any irreversible negative feedbacks or counter-defense against system collapse.

The share to TEK holders in the pre-trade period served in large part to reward whaling captains for their managerial and TEK related skills. A representative measure of the share to capital is found in examining more closely Figure 2 together with Table 1; the harpooner and the captain are each rewarded with additional portions of the whale, and the captain has discretion over communal distributions at festivals[15]. Note that all communities do not share in the same way, but that the share to TEK of the whale itself is substantial, upwards of 30%.

The information in Table 1 and Figure 2 is derived from a recent report on bowhead whaling practices in Inuit communities, (Associates, 2018). From this, in combination with the overall resource base which requires much less group management or specialized TEK, I estimate that the overall share allocated to capital is a bit less than 6%.[16]

The dynamics of the parameterized model suggest an eventual biological equilibrium with the resource base, human population and TEK human capital co-existing, such as illustrated in Figures 4 and 5. The system is somewhat resilient to changes in parameters and conditions, including the ranges of uncertainty for the ecosystem biomass, but can result in either depletion of the resource base and subsequent extinction of the upper trophic levels, or failure to maintain the upper trophic layers, even with intervention in the amount of the ecosystem harvested or the share to TEK with large enough changes in e.g. harvestability or the resource base, as one might expect.

[insert figures 4 and 5 here]

---

[15] Note that not all communities might share in exactly the same way, and/or that other marine mammal species may be divided in different shares.

[16] Note that not all communities share in exactly the same way, and/or that other marine mammal species may be divided in different shares; Associates (2018) illustrates several configurations across communities.

Increasing the total resource share to capital to about 30% increases the overall human population in the system, with increases in both upper trophic populations. Between 30% and 35%, an inceased share increases the TEK holding population at the expense of the laborer population, and above 35%, both begin to decline until they die out completely. This relationship may shift considerably depending on the extent to which the TEK population is reliant on the laborer population for sustenance in return for its useful knowledge, but the premise remains the same: productive useful knowledge can create capital that uses less of the resource base to support more at upper trophic levels, but it must truly be productive in order to not just benefit the capital class, but to sustain the socio-ecological system at all.

## 4.2 Resource extraction without compensation: whaling and walrusing

In the 1800s, the stability of the system was tested by the foreign exploitation of resources from outside the socio-ecological system. This occurred on a large scale through commercial whaling and walrusing in the Atlantic and Pacific, as described above.

Initial high takings dwindled down and did not recover; this was consistent with high rates of overexploitation of the resource.[17] Figure 6 illustrates the harvests for the two most essential species, Bowhead whale and walrus (Atlantic and Pacific). Since the Thule Inuit date back to at least 1000 AD in the western Arctic, I assume that the introduction of commercial whaling occurred after a stable equilibrium path of extensive growth existed in the Inuit socio-ecological system. I introduce the harvest estimates summarized in Tables 6 and 7, and shown in annual figures in Figure 6, into the system as drawdowns of the resource base. This allows direct examination of their impact on the upper trophic (human) populations.

[insert figure 6 about here]

Harvest technologies from 19th Century commercial whaling ships far outpaced the reproduction rates of the whales, at least at higher whale densities where whales were relatively easy to catch. The system

[17] In each location, as many have noted, initial high takings accounted for a significant portion of the whales that would ever be caught there (Allen & Keay, 2006; Bockstoce, 1986; Kruse, 2017)

dynamics show that commercial harvesting, without caloric compensation for the Inuit, would rapidly render the socio-ecological system infeasible. In the simulation, the resource base is essentially depleted by the mid-1850s[18], with the human population's subsequent demise soon after (Figure 7). This timing, adjusted slightly later for the later start in the western Arctic, matches well with what is known in the historical about die-offs and/or migratory moves provoked by whaling (Bockstoce, 1986; Burch, 2012).

[insert figure 7 here]

It may be that the initial estimate of the resource base is too conservative; however, a doubling of the resource base only delays the depletion by 20 years. This is at least partly due to the assumption that the Inuit population is already well established and using the resource base to support itself at capacity. If, instead, one assumes that the commercial extraction of the resource base and the upper trophic level's entry into the system begin together, then this amount of commercial whaling, if it stops after a bit more than 100 years as it did, only delays reaching the eventual steady state. That is, new ecosystems without human dependents may in fact be overexploited for a short time and then recover to successfully produce healthy socio-ecological systems.

On the other hand, consistent low level siphoning off of the resource base over time reduces the human population in predictable but informative ways. At levels greater than the ecosystem growth rate, the resource base and the human population disappear, at levels greater than the human intrinsic growth rate, the human population disappears; at levels below this, the long run human population is in effect traded off for the commercial harvest.

[insert table 8 here]

The ultimate benefit or loss of this tradeoff to the socio-ecological system depends on the terms of trade. The extremely poor terms of trade between commercial whalers and Indigenous communities were woefully inadequate to compensate for the reduced resource base and dependent human population.

[18] Due to the spatial differentiation and different starting times in Pacific and Atlantic whaling, the actual depletion in the western Arctic came a bit later.

From a global standpoint, the high rate of return on the early commercial harvests is not in question; the wealth transfer from Inuit communities to the whaling centers of the Netherlands, the UK, and Nantucket and New Bedford, MA was undoubtedly in excess of the approximately 2.3% human growth rate, at least until discoveries and advancements in substitute oils that began in earnest by the 1850s (Davis, Gallman, & Gleiter, 1997). New Bedford, MA was frequently identified as the wealthiest town in the United States, but as one historian puts it, this may have been only because "most of its low paid workers lived at sea" (Lindgren, 1999), a statement that succinctly sums up how the lay system of 19th Century American whaling[19] and the slow progress of ship technology served to defray costs from capital to the laborer population in the socio-ecological system of commercial whaling.

There is more question about the long run productivity of this capital, particularly that which built up in New Bedford. The industry was in the hands of approximately 50 extended families, many of whom chose to re-invest in the industry with new ships after repeated losses at sea in the 1870s, by which time it was clear that the long run prospects for oil were in decline and costs were rising due in large part to increasing scarcity of whales.[20] Thus some of the converted natural capital ended its days, at the bottom of the sea, without contributing further to greater economic gains. With some irony, the ships that were lost in ice in the Arctic (before sinking) were generally heavily scavenged by Inuit communities, which served to return a little of the depleted resource base to its initial stewards in the form of metals, timbers and other stores {Davis, 1997 #154; #77;Lindgren, 1999 #153;Bockstoce, 1986 #109}.

## 4.3 Mutually beneficial trading with external systems: fox fur trading

Arctic fox (*Alopex lagopus*), also known as white or ice fox, was one of several fur bearing species for which Canadian and American interests, represented in large part by the Hudson Bay Company, traded with northern Indigenous peoples; while muskrat (*Ondatra zibethicus*) and beaver (*Castor canadensis*)

[19] The lay system paid whalers portions of the ship's profits rather than wages, with many of the needed provisions for the average 2-4 year long voyages coming out of the profits and pay directly.
[20] Much of the remaining whaling capital went to fund a new textile industry in New Bedford.

dominated this trade, these species were not present above the tree line; Arctic fox was the primary species traded with the Inuit[21].

### 4.3.1 Benefits from trade: expansion of the potential value of an ecosystem component

As noted, Arctic fox were not regularly hunted or consumed by Inuit before commercial interests made them valuable. TEK holders, however, understood Arctic fox behavioral patterns and could identify Arctic fox dens readily. The fox has also now been identified by academic science as a key part of ecosystem productivity in the tundra (Gharajehdaghipour, Roth, Fafard, & Markham, 2016).[22]

While we do not know exactly what TEK holders knew in the late 1800s about the bigger role fox dens played in the ecosystem, two facts make it likely that TEK holders were at least partially aware of the fox's place in the ecosystem. These are (1) that fox dens are so vibrantly differentiated from the rest of the tundra that they are easily identifiable from a distance, and even from the air (Garrott, Eberhardt, & Hanson, 1983), and (2) that when trapping did begin, harvest numbers were high, indicating ease in locating and trapping them (Kaiser and Parchomenko, 2018). They rose particularly quickly (a 10-fold increase in catch per unit of effort, according to Bockstoce (2018)) after the 1860s introduction of steel traps in the Western Arctic.

In reverse, as prices have collapsed for fox furs, a 2011 survey of Inuit recounts that while 91% of older Inuit hunters (35-49) report that they know where to set fox traps *and why to set them there*, only 46% of younger (18-34) Inuit hold this TEK (Pearce et al., 2011). The return to these TEK holdings has fallen significantly, just as it rose when furs became valuable through trade. The fox fur trade provides an explicit example of 'capital broadening' from more dispersed ecosystem use.

---

[21] Both demand and supply generated a rather cyclical pattern to wild fox harvest. With many substitutes, Arctic fox's demand differentiation came in its ability to be easily dyed. This made it particularly popular in the 1920s. Arctic fox fur is not highly durable, however, dampening demand in other periods. At the same time, Arctic fox was rather easily cultivated on island farms. In the Aleutian Islands, a few hundred farms were set up there in the 1920s, with the resultant product lowering prices (Bailey, 1993). Furthermore, Arctic fox are scavenger-predators whose populations are already cyclical in connection to small mammal (vole, lemming, etc.) populations (Obbard et al., 1999). I set aside these interesting dynamics and concentrate on the fox as a small scale component of the Arctic coastal ecosystem.

[22] In particular, fox dens promote plant growth that increases nitrogen on the tundra, in turn fostering additional plant growth and animal fodder. This essentially creates garden oases that support and expand the ecosystem's productivity.

The fur trade could provide an alternative outcome involving system exit: a ‘pull-exit’ into the commodified world of trade goods and cash economy. The goods acquired generally consisted of metal tools for hunting and cooking (e.g. kettles, pots, guns, traps); food items, primarily grains, coffee and tea, and sugar, or consumption goods in the form of tobacco, more decorative than functional articles of clothing, and alcohol.

The first two categories could facilitate increases in the catchability of the existing ecosystem and reduce the dependence upon it. Following from the above discussion, the amount of food calories needed to maintain the system can be calculated for the missing ecosystem components; in the case of the fox, the caloric benefits are low. If there were no whale and walrus hunting, the removal of the fox population in exchange for other goods would represent only a 0.0166% decrease in the untouched resource base, or 0.05% of the resource base at its pre-contact use levels; this is well within the range that the system could accommodate, despite its limitation to an annual reduction of 0.37% of the initial population base, or 0.5% of the resource base at its pre-contact level (Table 8). The minimum acceptable terms of trade for the entire fox population could be as low as 4 billion calories,[23] or the equivalent of just 11 bowhead whales (see Appendix D).

A common exchange in the early period included a range of furs in trade for e.g. copper tea kettles, tobacco, tea, and hunting knives, but this trade eventually expanded to include e.g. flour, rifles, and ammunition. Even with the mediocre terms of trade, given that these furs would fetch more than 10 times this value in the global fur market (Bockstoce, 2009, 2018), the caloric threshold could clearly be met either directly or through increased technological catchability due to the low opportunity cost of the fox as a caloric source.

### 4.3.2 Costs of trade: the introduction of new diseases through trade

At the same time, however, foreigners introduced diseases that may have killed off as much as 90% of some Inuit populations, with 60% also being a commonly noted figure (Burch, 2012). In the system presented here, if disease had acted alone upon the system, an increase in the death rates of the upper

[23] This is assuming no ecosystem interdependencies between the fox and other necessary components of the ecosystem.

trophic levels of more than 2.37 times the initial death rate would lead to the extinction of the Inuit population, regardless of any harvesting – and if the death rate remained high but below this threshold, a new long run equilibrium path would exist with a significantly lower human population (Figure 8).

[insert Figure 8 about here]

As seen in Figure 8, the increased death rate frees up the resource for other uses. This extends the time it would take for uncompensated whaling and walrusing harvests to extinguish the Inuit populations by a few years compared to the conditions explored in Figure 7, but the ecosystem recovery comes too late even for the dwindling population, as shown in Figure 9.

[insert figure 9 here]

### 4.3.3 Ambiguous impacts of trade: Technological advances

Rapid technological advances achieved through trade increased the ease with which ecosystem harvest could occur. If the additional harvest is fully translated into population growth, the system cannot sustain the population growth and the technological advances serve to deplete the resources. With virtually no wealth storage within the system beyond TEK holders' bodies themselves, the additional harvest must be translated into traded value from outside the system if it is to be absorbed. As shown in Table 8, the system can accommodate about 0.5% of harvest while maintaining upper trophic levels, but at a cost of an approximate 62% reduction in the population. If the calories are made up in trade, then the human population can continue at the initial level and to harvest the ecosystem, but with the cultural shifts that come from the new hybrid resource base of introduced foods and technologies.

For additional growth to occur at initial human population levels, storable wealth and useful knowledge that fits the new resource base must accompany the introduced calories.

#### *4.3.3.1 Technological advance with no disease and no commercial harvest of marine mammals*

Technological advances that increase catchability and the convertibility of the resource to TEK ten-fold, with no other changes, introduce instability through long predator-prey cycles as shown in Figure 10.

[insert figure 10 here]

These cycles can be expanded or contracted with the existing controls that can shift the resource base to trade or to TEK development, but a stable equilibrium cannot be restored within the confines of the existing socio-ecological system. For this to occur, technological advancement can only be so great; if the growth in catchability and convertibility are limited to 2.5 times the initial rates, keeping 5.87% as the share to TEK holders and 0.05% for trade (in non-food items), after many generations the system could settle down to a higher human population with a lower ecosystem base, as shown in Figure 11.

[insert figure 11 here]

#### *4.3.3.2 Technological advance with disease but no commercial harvest*

If the new technologies introduced increase both the technology coefficient on TEK and the catchability by a factor of ten, as suggested for fox trapping efficiency, there is no commercial harvest, and population die-off begins and continues at a high rate, then the system avoids total collapse, but cannot automatically stabilize in the long run, as shown in Figure 12.

[insert figure 12 here]

## 5. Discussion and Conclusions

Overall, the model performs very well at matching what we know about the evolution of Inuit communities over time, as well as providing clearly delineated opportunities to investigate meaningful counterfactuals about the roles of disease, technological change, and trade.

The long run evolution of Inuit societies provides opportunity to investigate tradeoffs in a resource-dependent society between increased trade, which can secure a wider variety of goods and technology, and increased capital formation, in the form of Traditional Ecological Knowledge – i.e. the 'useful knowledge' associated with the resource base. Historically, the most valuable international commodities in Inuit communities have been large marine mammals, particularly whales, walrus, seals, and Arctic fox. The similarities and differences between these components of Arctic ecosystems assist in developing a greater understanding of these tradeoffs.

Large marine mammals and seals were treated as open access natural resources, originally because Inuit communities were too small, and whaling too difficult, to require harvesting restrictions beyond what the system already imposed. TEK regarding harvest and use of the marine mammals for perpetuation of the system was high and facilitated a limited development of an elite based on managerial knowhow for coordinating the harvests. The system did not require development of secure property rights to marine mammals or governance of the harvest, so TEK holders did not invest in such costly activities. The sustainable elite was very low due to the need for any transfer of the resource base to TEK to be at least as productive as simply using the resource base for subsistence without capital deepening; the lack of wealth storage (outside of TEK) in particular meant that the system afforded few if any extractable rents that were not in turn used to increase either the resource base or its catchability and productivity.

When foreign whalers entered the systems, a documented tragedy of the commons ensued. The marine mammal resource base, essential to the physical survival of Inuit communities from the Bering Strait to Baffin Bay who had served as efficient stewards to the ecosystem under their systems of useful knowledge, was siphoned off in ways that Inuit could not unilaterally compensate, leaving population decline and system exit (including migration and replication in more distant locales) as the primary responses.

An alternative response was to invest in ‘natural capital broadening and deepening,’ or creating an increase in the intensity with which other components of the ecosystem came into direct human use. This capital enhancement worked particularly well when combined with trade imports for technologies such as firearms and steel traps as inputs and trade exports that had little value to the Inuit. Fox fur trapping provided such an opportunity. In this case, the application of existing TEK to new components of the resource base could be implemented with new technologies, providing both benefits and risks. While TEK included significant knowledge about where to find Arctic fox, a lack of particular usefulness to the socio-ecological system combined with high costs of acquiring foxes before the arrival of steel traps meant that this component of the ecosystem was little utilized; trade with foreigners who both wanted the fur and had much more difficulty engaging directly in the ecosystem for trapping had more win-win potential. At the same time, the introduction of European goods in trade generated new pressures for what I term “pull-exit” from the system. Pull-exit reduced direct and indirect dependence on the socio-ecological system; directly, individuals had access to traded goods, and indirectly, this reduced the reliance on coordinated hunting of large marine mammals.

Simultaneously, "push-exit" from the system came from the depletion of the sustaining resource base without adequate compensation. The failure to secure rights to open access marine mammals stemmed in part from the communities' lack of need for harvest governance; resource conservation, useful knowledge, and governance in Inuit socio-ecological systems had always relied on no-waste, that is, full use of the animals that were harvested, rather than limiting harvest. This initial failure to secure rights in the face of new users of the resource base then fed into declining usefulness of the whaling-focused TEK that had generated the small amounts of community elites that had existed. In turn, as Inuit communities have progressed into greater integration with the foreign powers of the US, Canada and Denmark, a lack of historic capacity with relevant governance mechanisms that could have led to development of coordinated and complete responses, establishing equitable rights to the ecosystem benefits, has further driven system exit.

The net impact of this socio-ecological system exit on both Inuit and global well-being remains uncertain, but the lack of ownership and subsequent control over the ecosystem and its resources that has driven much of the resource decline, and 'push-exit' has at the very least worked against the cultural values of Inuit communities. It is today introducing a new set of concerns in which global and local values are not aligned. A positive development in response to this has been a move toward increased co-governance of marine mammal resources in particular.

The number of relatively intact Inuit communities from Alaska through to Greenland, never large, is certainly smaller; as noted for example, Burch (2012) estimates that Alaskan populations declined by 60% from 1850-1900, and communities that are not regional centers with considerable foreign populations remain small today (fewer than 400 people on average) (Associates, 2018). TEK holdings remain primarily represented by a small share of whaling captains, who now take on additional leadership responsibilities. In Alaska, for example, in the eleven remaining whaling communities, there are 155 registered whaling captains from a combined population of 6,677, or 2.3% of the population (Associates, 2018).

On the other hand, Inuit congregating in regional centers mean that the current population estimate for combined Inuit populations is growing, and is now about 135,000 people. Though it is difficult to be certain, this is likely at least as many Inuit as 200 years ago, before intensive foreign incursion into Inuit communities. This is in contrast with most evidence about broader native population decimation in the Americas in general following European contact.

The Arctic fur trade created vast wealth (and power) for companies like Hudson Bay Company; it generated thousands of jobs and dollars in revenue in towns like Leipzig (a global center for the industry (Declercq, 2017)) over the late 19th until the mid-20th Century, including over 2500 Alaskan fox fur farms in the 1920s (Bockstoce, 2018), but these in turn degraded the ecosystem for other purposes and all users (Croll, Maron, Estes, Danner, & Byrd, 2005). While these global benefits and costs are mainly beyond the scope of this model and story, I include mention of them here to remind readers of how the Inuit story fits into the broader cycles of globalization and the role of marketization in simultaneously degrading and expanding ecosystems and their values to society.

Evolving global values for the natural capital resource base of Inuit communities continues to influence development and system exit today. The bottoming out of seal and fox fur markets, and international regulations to stop industrial scale seal hunting, has reduced Inuit communities' access to tradable natural capital from the ecosystems (Graugaard, 2018; Wenzel, 1996); remaining 'in' the socio-ecological system in this framework allows domestic consumption and use of the resource base but not broader gains from mutually beneficial trade.

At the same time, large marine mammals have become more valued alive at the global scale than the products one can harvest from them. This has switched Inuit concerns from not being able to harvest and use this component of the system due to their lack of availability, to not being able to harvest it due to global treaty negotiations forbidding it, e.g. under the International Whaling Commission (IWC) and/ or the EC-Seal Products dispute (Conconi & Voon, 2016). While Inuit communities have established limited rights to harvest, and have harvested approximately 1600 bowhead and 5000 minke whales[24] since 1985 (an average of about 50 bowhead and 150 minke whales per year), these quotas have required renegotiation and significant defending; until the 2012 formation of the Ad Hoc Aboriginal Subsistence Whaling Working Group, there was no cohesive governance voice at the IWC. Since that time, the group has strengthened Indigenous rights and claims; at the September 2018 IWC meetings, an agreement was reached that current catch limits would be automatically renewed as long as a mutually agreed upon process was met in the interim (Commission, 2018).

Finally, though the disruptions brought through trade and technology have been both severe and abrupt, the model and the Inuit experience agree that dismantling this small-scale socio-ecological system in favor of greater integration of the resource base with world markets has been a lengthy and ongoing process. This has worked to preserve cultural identities to an extent where a hybrid socio-ecological system may successfully endure. TEK that was specific to the challenging Arctic environment served to extend the time-line available for long run reformation of communities; as the climate provided a strong barrier to those without TEK capital, both the direct sustenance from TEK for marine mammal hunting and the indirect sustenance from the fox fur trade assisted in preserving Inuit culture amidst significant pressures from globalization, including disease. Inuit culture, having passed through a challenging crucible, may now spread beyond the Arctic in ways that create a new socio-ecological system with a broader resource base. Some direct evidence of this can be found in e.g. the reports that bowhead whale harvests today are being shared with Inuit living in urban areas at considerable distance from the socio-ecological system's resource base.

[24] Minke whale harvest primarily takes place in Greenland and waters to the East of Greenland.

# Tables

**Table 1: Division of bowhead whale by TEK capabilities (present day). Compiled by K. M. Hansen from Associates (2018).**

| Location | Captain(s) | Harpooner | Successful crew | Assisting boats | All boat crew | Community (at captain's discretion) | Assisting community |
|---|---|---|---|---|---|---|---|
| **Utqiaġvik**<br>**Nuiqsut**<br>**Kaktovik**<br>**Wainwright** | ½ Jaw/Baleen<br>Blowhole<br>Mid-section<br>Fresh meat<br>Ventral flanks<br>Between flukes and ventral flanks<br>Flukes | 1 flipper | Mid-section | ½ Jaw/baleen | 1 Taliguq (flipper)<br>Silviik<br>Qimigluich | Ventral Flank<br>Mid-section<br>Tongue, heart, brisket, kidneys, small intestine<br>Ventral flanks<br>Between flukes and ventral flanks<br>Flukes | Silviik<br>Qimigluich<br>Mid-section |
| **Point Hope** | Ventral flanks<br>¼- ½ baleen<br>Tip of flippers | | Qimigluich<br>½ baleen<br>Part of flippers | Silviik<br>Jaw area with tongue and maktak<br>Mid-section<br>(¼ baleen) | Head section - maktak only | Ventral flanks<br>Flukes<br>Between ventral flanks and flukes | Area under the jaw |
| **Gambell**<br>**Savoonga** | Head/baleen<br>Flippers<br>Four pieces of maktak<br>Mid-section<br>Ventral flanks | | | | Area under the jaw<br>Silviik<br>Qimigluich | Small meat pieces | |

**Table 2: Variables pertaining to capture and sharing of the composite resource base**

| Variable | Description | Potential determinants |
|---|---|---|
| $R_t$ | Composite resource base (ecosystem) | Intrinsic growth, carrying capacity, laborer population, TEK holdings, resource intensity coefficient, catchability coefficient |
| $N_t$ | Human laborer population, dependent on resource base | Intrinsic growth, death rate, intraspecific coefficient, resource base, TEK holdings, resource intensity coefficient, catchability coefficient, share to trade, share to capital. |
| $K_{2t}$ | TEK holdings (population), dependent on the human and resource populations | Technology parameters, resource intensity coefficient, catchability coefficient, share to trade, share to capital, Resource base, Laborer population |
| $c$ | Technologically determined catchability coefficient on the resource population | Control variable; maximum varies with technology |
| $\gamma(K_2)$ | Resource intensity coefficient (TEK dispersion factor) | TEK holdings |
| $s$ | Share of the resource to trade | Control variable |
| $\varphi$ | Gross share of the resource to capital | Control variable |

**Table 3: Valuation variables**

| Variable | Description | Potential determinants |
|---|---|---|
| $V_{kt}$ | Unit value of capital | Exogenous |
| $P_t$ | Unit value of traded resource | Exogenous |
| $V_t$ | Unit value of consumption | Exogenous |

**Table 4: Cost Variables for harvest and governance**

| Variable | Description | Potential determinants |
|---|---|---|
| $w_c$ | Marginal cost of resource harvest to Inuit | Resource base, TEK holdings |
| $w_\varphi$ | Marginal cost of governing share to capital | Share to capital, Laborer population |
| $w_s$ | Marginal cost of governing share to trade | Share to trade, Laborer population, external pressure from commercial harvest |
| $w_\gamma$ | Marginal cost of increasing ecosystem dispersion /resource intensity | Resource intensity coefficient, Resource base, Laborer population, TEK holdings |

**Table 5: Technology, growth, depreciation and capacity variables**

| Variable | Description |
|---|---|
| $\chi$ | Intraspecific competition coefficient |
| $A$ | Technological transformation coefficient for TEK creation |
| $\xi$ | Technological transformation parameter for TEK creation |
| $g_R$ | Intrinsic growth rate of resource base |
| $g_N$ | Intrinsic growth rate of human population |
| $K_1$ | Carrying capacity of the resource base (ecosystem) |
| $d$ | Death rate of human (laborer) population |
| $\delta$ | Depreciation of TEK (death rate of managerial elite) |

**Table 6: Bowhead whale populations and commercial use in Inuit Arctic**

| Stock location (Bowhead) | Pre-contact stock estimate | Years of commercial harvest | Cumulative catch estimate | Stock estimate at low. | Est. repro-ductive rate | Sources |
|---|---|---|---|---|---|---|
| Bering Sea Western Arctic | 20,000 (14,000-35,000) | 1848-1914 | 16,600 | 3,435 | 0-7% | (Bockstoce, 1986; Conrad, 1989; Woodby & Botkin, 1993) |
| Hudson's Bay | 580 | 1860-1914 | 688 | ~0 | 0-7% | Ross (1974);Woodby and Botkin (1993) |
| Davis Strait | 18,000 | 1700s-1911 | 10,012 | 300 | 0-7% | Woodby and Botkin (1993); Gross (2010);Allen and Keay (2006) |
| Greenland-Spitzbergen fishery (*excluded*) | 52,477 | 1611-1911 | *uncertain* | 1,000 | 0-7% | Allen & Keay (2006) |

**Table 7: Walrus populations and commercial use in Inuit Arctic**

| Stock location (Walrus) | Pre-contact stock estimate | Years of commercial harvest | Cumulative catch estimate | Final stock estimate | Est. repro-ductive rate | Sources |
|---|---|---|---|---|---|---|
| Western Arctic (Pacific walrus) | *~300,000* | 1849-1950s | 148,250 (to 1914) | 65,500-94,000 | 2-5% | Bockstoce (1986); Fay, Eberhardt, Kelly, Burns, and Quakenbush (1997) |
| Eastern Arctic (Atlantic walrus; Foxe Basin, Hudson Bay, Baffin Bay) | *Unknown, est. 200,000* | 1885-1928 | 41,300 | 15,500 | 2-5% | (Born, Gjertz, & Reeves, 1995; Stewart et al., 2014) |

**Table 8: Feasibility of constant commercial harvest of Inuit ecosystem**

| | Commercial extraction starting in 1819 | | | | | |
|---|---|---|---|---|---|---|
| R | 8323 | 8323 | 8323 | 8323 | 8323 | 8323 |
| N | 20 | 20 | 20 | 20 | 20 | 20 |
| K2 | 1 | 1 | 1 | 1 | 1 | 1 |
| Commercial harvest | 0 | 2.4 | 4 | 53 | 89 | 120.5 |
| (as % of initial R) | 0.00% | 0.03% | 0.05% | 0.22% | 0.50% | 1.00% |
| | Conditions after 1000 periods | | | | | |
| R | 8319 | 8319 | 8319 | 8272 | 4526 | depleted |
| N | 20.5 | 20.3 | 20.1 | 15.5 | 7.7 | depleted |
| K2 | 1 | 1 | 1 | 1 | >1 | depleted |

# Figures

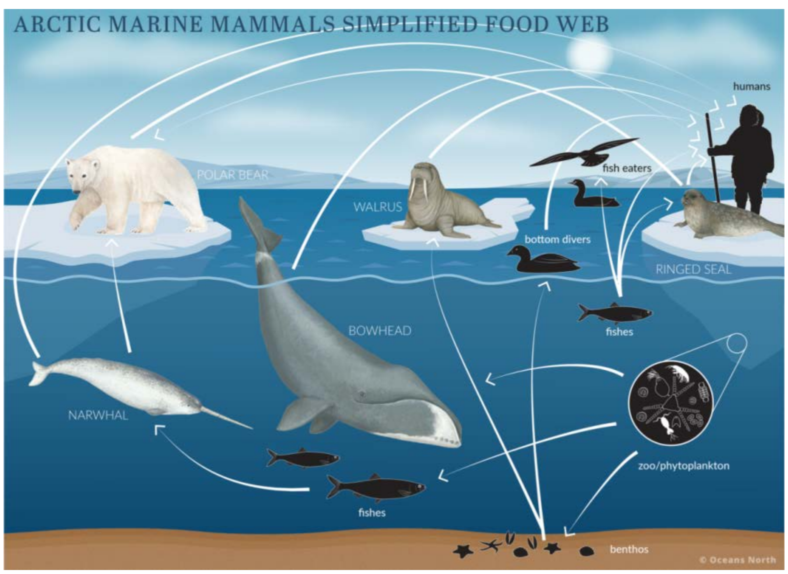


**Figure 1: Simplified Inuit coastal food chain. Image credit: Oceans North Marine Atlas**

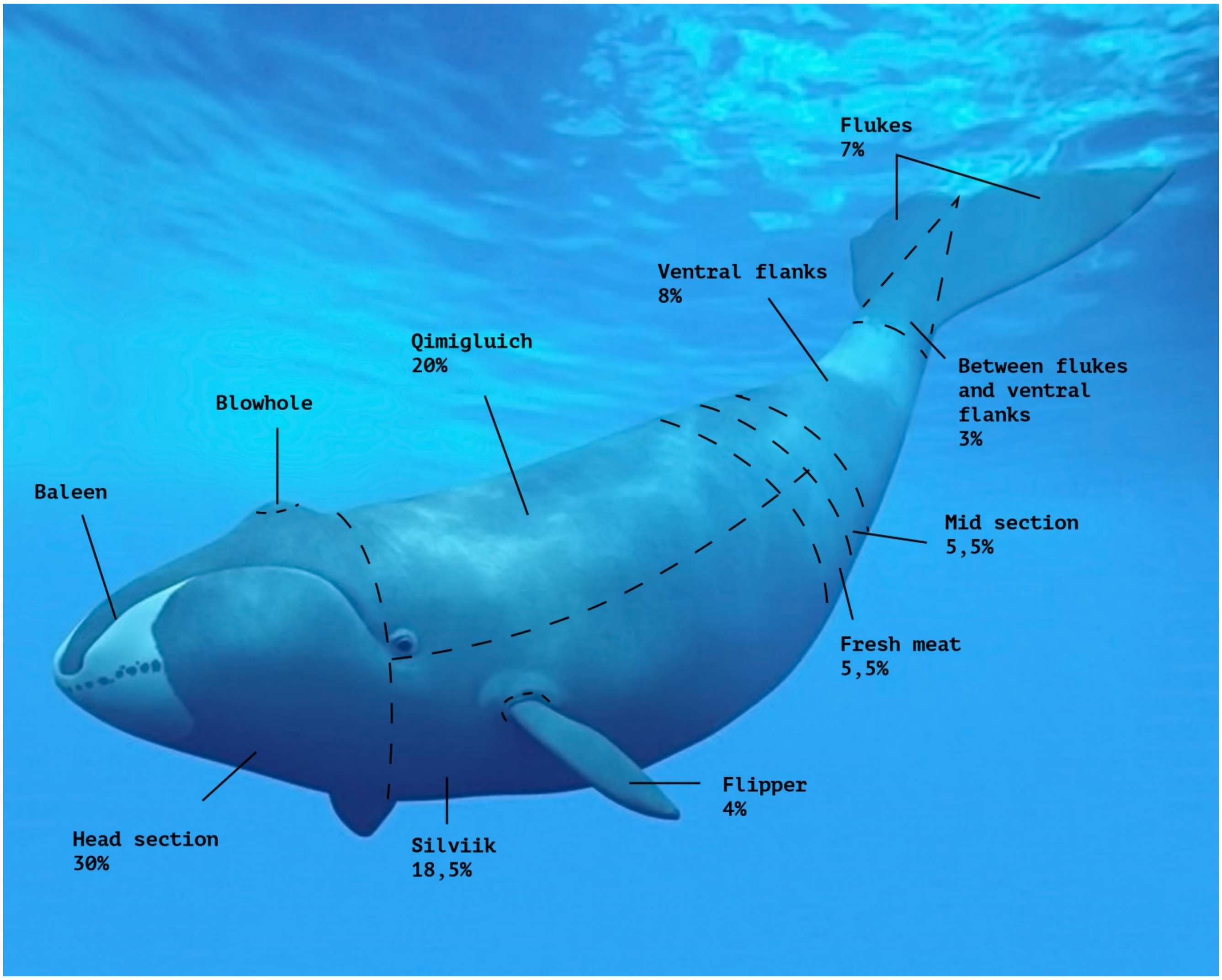


**Figure 2: Division of bowhead whale, with approximate portions. Photo: creative commons license; Segmentation and pixelated calculation of relative sizes, K. M. Hansen.**

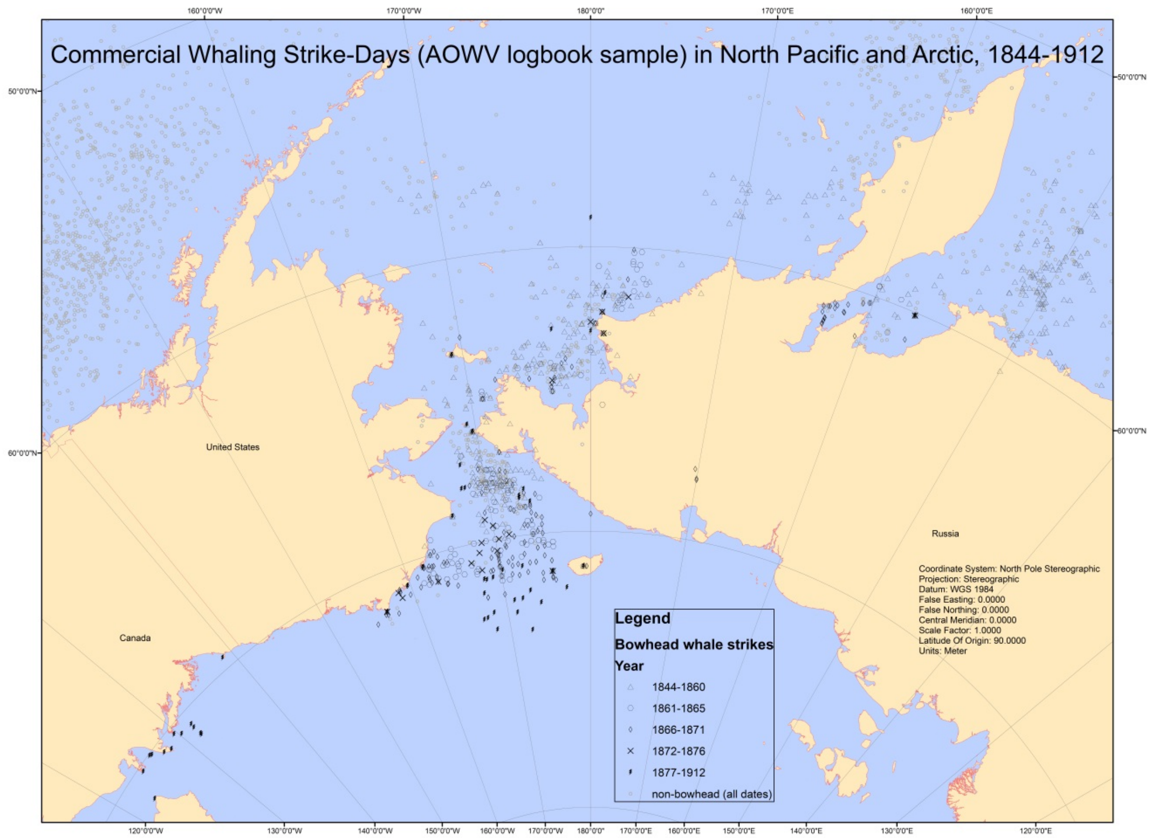


**Figure 3. Spatial sample of American Commercial Whaling Strikes in the Pacific Arctic, 1844-1912 (AOWV database)**

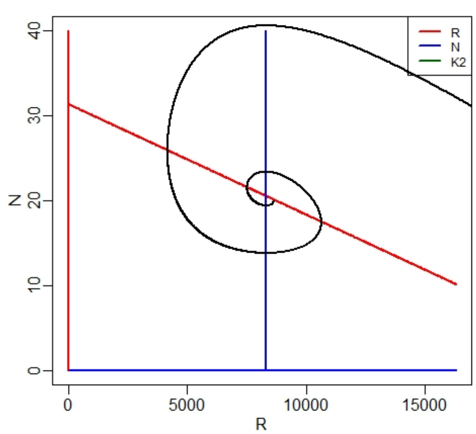


**Figure 4: Population dynamics in stable socio-ecological system**

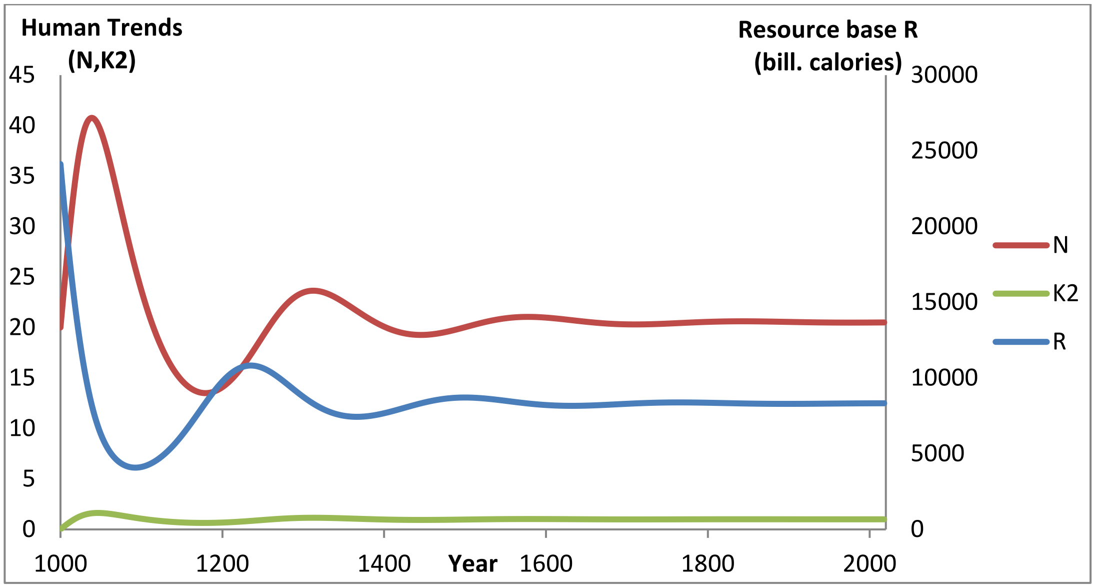


**Figure 5: Populations over time in stable socio-ecological system**

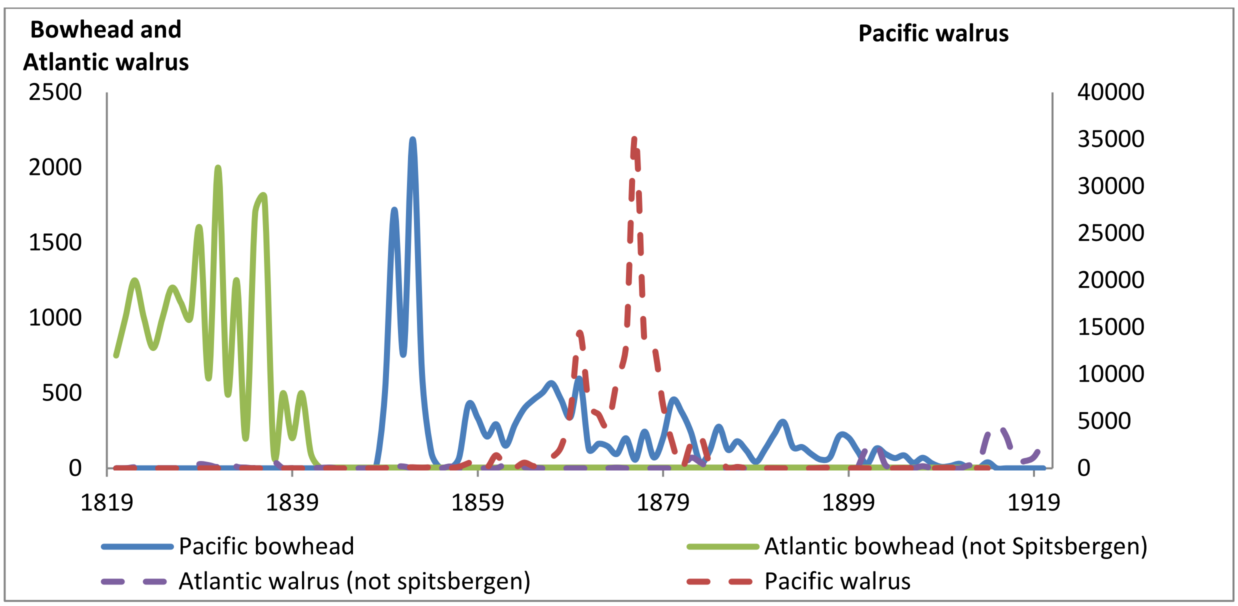


**Figure 6: Commercial bowhead whale and Pacific and Atlantic walrus in the 19th and early 20th Century.**

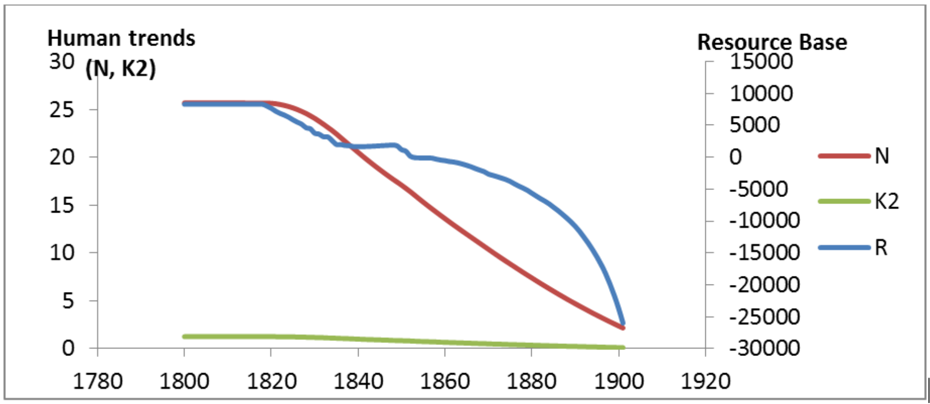


Figure 7: System depletion from commercial harvests, 1819-1919.

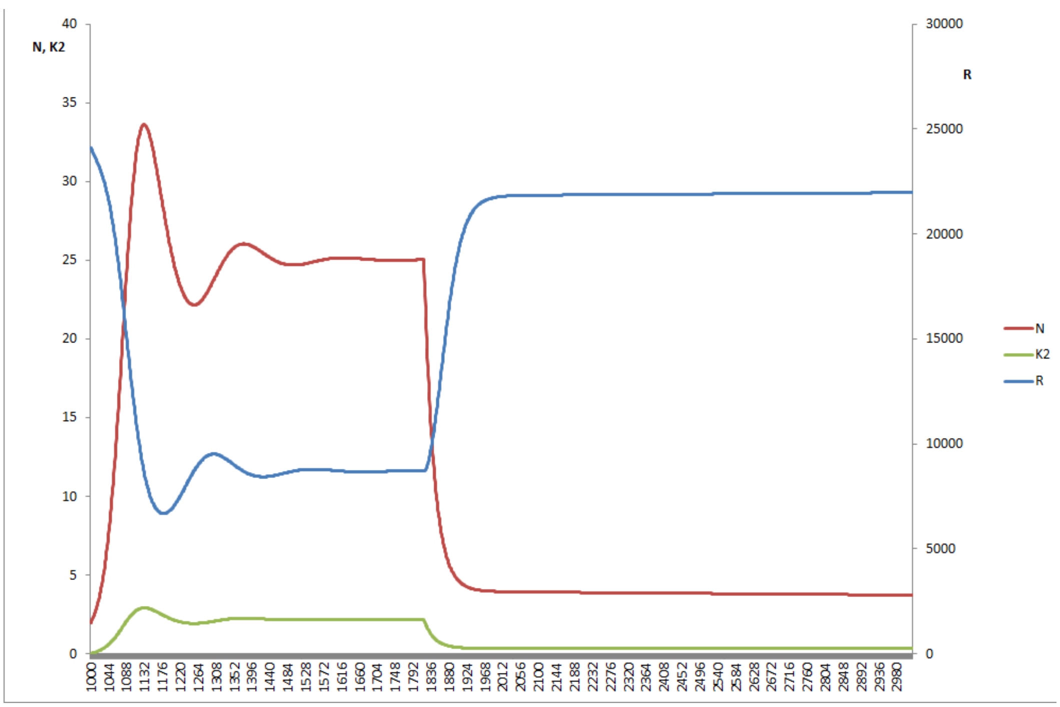


Figure 8: Introduction of disease with increase in human death rates 2.37 times higher than initial conditions in year 1819.

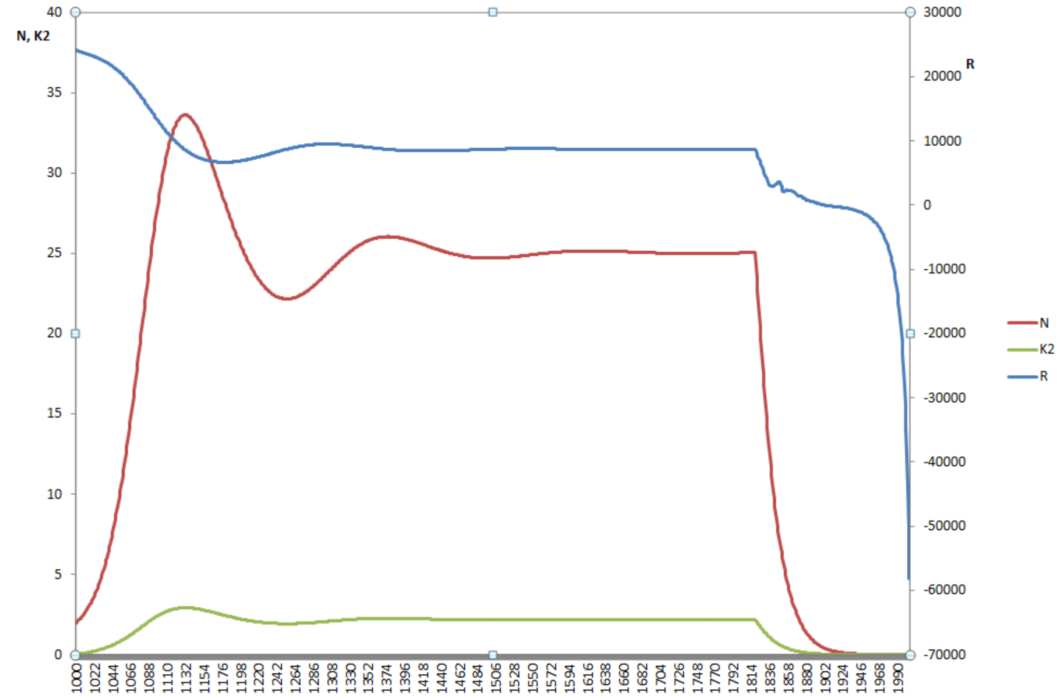


**Figure 9: Commercial harvest with disease at 2.37 times the initial rate results in extinction of Inuit trophic levels.**

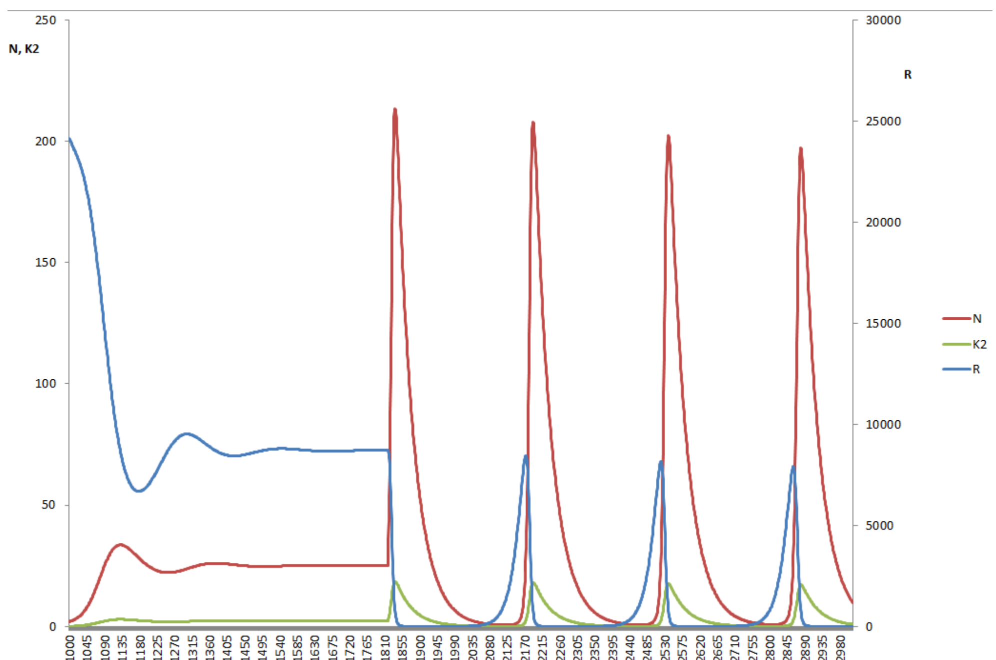


**Figure 10: Technological advances destabilize the socio-ecological system**

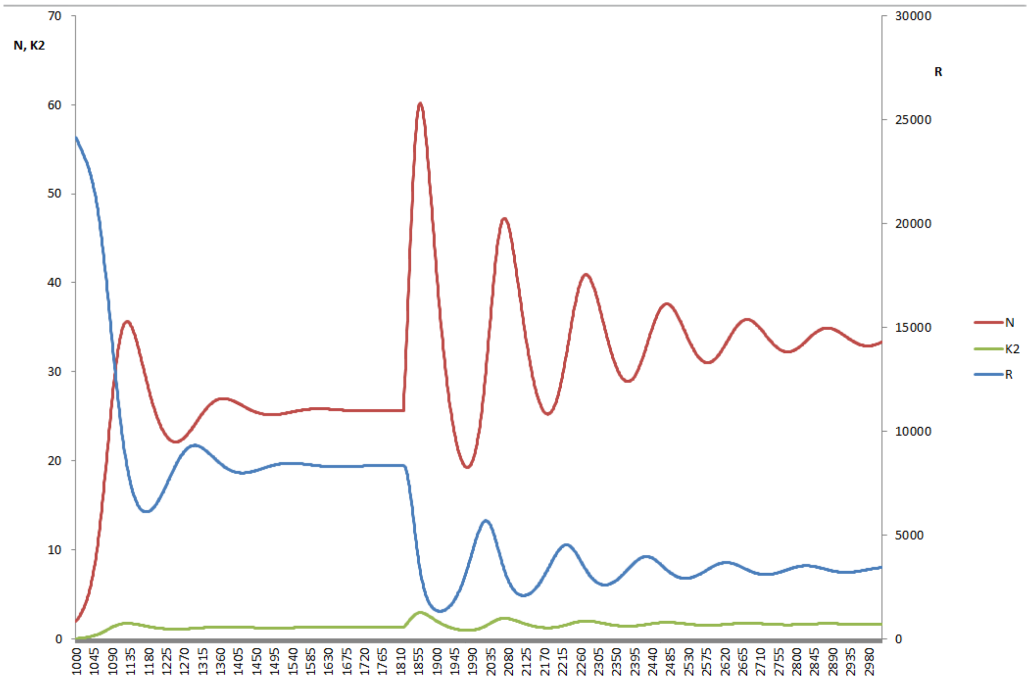


**Figure 11: Increased technology, within limits and without additional disturbances, can result in higher exploitation of the resource base and greater human populations.**

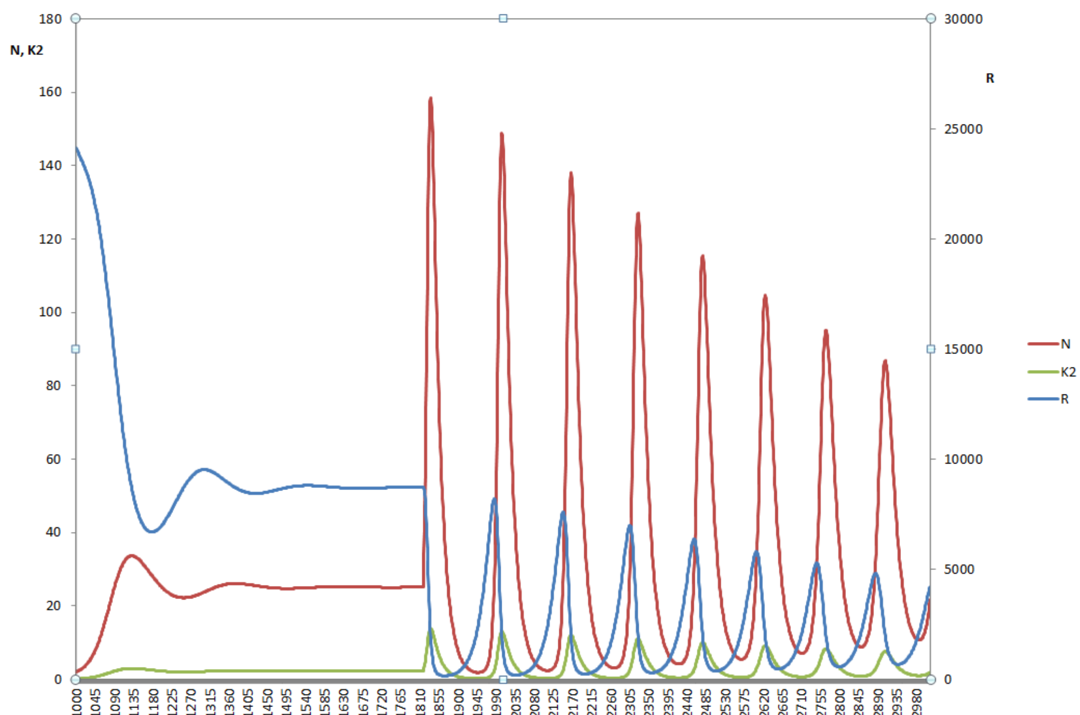


**Figure 12: The introduction of better harvesting technology and know-how alongside higher death rates leads to long run system instability**

## Acknowledgments

Thanks to Alexej Parchomenko and Kirstine Marie Hansen for research assistance. Thanks to Melina Kourantidou, Charlotte Nyborg Kristensen, Andreea-Laura Cojocaru, James Roumasset, Sarah Jane Harper, and participants of the International Arctic Social Science Associations Conference (2017), the Neo-Malthusian Workshop at Jesus College (2018), the University of Alaska Anchorage Economics Seminar Series (2019), among others, for fruitful questions, comments, discussions and encouragement.

## Funding

The Independent Research Fund Denmark provided funding a research travel stay at the University of British Columbia that has facilitated this research (grant number 8046-00056B).

## Works cited

Allen, R. C., & Keay, I. (2006). Bowhead Whales in the Eastern Arctic, 1611-1911: Population Reconstruction with Historical Whaling Records. *Environment and History, 12*(1), 89-113.

Anderson, J. (2011). From Alaska to Greenland: A comparison of the Arctic Small Tool and Thule Traditions. *Totem: The University of Western Ontario Journal of Anthropology, 12*(1).

Aporta, C. (2009). The trail as home: Inuit and their pan-Arctic network of routes. . *Human Ecology, 37*(2), 131-146.

Arendt, B. (2010). Caribou to cod: Moravian missionary influence on Inuit subsistence strategies. *Historical Archaeology, 44*(3), 81-101.

Associates, S. R. B. a. (2018). *Description of Alaskan Eskimo Bowhead Whale Subsistence Sharing Practices, Including an Overview of Bowhead Whale Harvesting and Community-Based Need* Retrieved from Anchorage, AK:

Bailey, E. P. (1993). *Introduction of Foxes to Alaskan Islands - History, Effects on Avifauna, and Eradication*. (93). Homer, AK

Barr, W. (1994). The Eighteenth Century trade between the ships of the Hudson's Bay Company and the Hudson Strait Inuit. *Arctic*, 236-246.

Betts, M. W. (2007). The Mackenzie Inuit whale bone industry: raw material, tool manufacture, scheduling, and trade. *Arctic, 60*(2), 129-144.

Betts, M. W., & Friesen, T. M. (2004). Quantifying hunter-gatherer intensification: a zooarchaeological case study from Arctic Canada. *Journal of Anthropological Archaeology, 23*(4), 357-384.

Bockstoce, J. R. (1986). *Whales, Ice, and Men: The History of Whaling in the Western Arctic*. Seattle: University of Washington Press.

Bockstoce, J. R. (2009). *Furs and frontiers on the far north: the contest among native and foreign nations for the Bering Strait fur trade*. New Haven: Yale University Press.

Bockstoce, J. R. (2018). *White fox and icy seas in the Western Arctic: the fur trade, transportation and change in the early 20th century*. New Haven: Yale University Press.

Born, E. W., Gjertz, I., & Reeves, R. R. (1995). *Population assessment of Atlantic walrus (Odobenus Rosmarus Rosmarus L.)*. Oslo

Brander, J. A., & Taylor, M. S. (1998). The Simple Economics of Easter Island: A Ricardo-Malthus Model of Renewable Resource Use. *American Economic Review, 88*(1), 119-138.

Brewster, N. (2005). *The Inuit in Southern Labrador: A View from Snack Cove.* (Master of Arts), Memorial University of Newfoundland, St. John's. Retrieved from https://research.library.mun.ca/10206/

Burch, J., E. S. (2012). *Caribou Herds of Northwest Alaska, 1850-2000*. Anchorage: University of Alaska Press.

Cabak, M., & Loring, S. (2000). "A Set of Very Fair Cups and Saucers": stamped ceramics as an example of Inuit incorporation. *International Journal of Historical Archaeology, 4*(1), 1-34.

Carboni, O. A., & Russu, P. (2013). Linear production function, externalities and indeterminacy in a capital-resource growth model. *Journal of Mathematical Economics, 49*(5), 6.

Clark, C. (2005). *Mathematical Bioeconomics: Optimal Management of Renewable Resources, 2nd Edition.*

Coltrain, J. B. (2009). Sealing, whaling and caribou revisited: additional insights from the skeletal isotope chemistry of eastern Arctic foragers. *Journal of Archaeological Science, 36*(3), 764-775.

Coltrain, J. B., Hayes, M. G., & O'Rourke, D. H. (2004). Sealing, whaling and caribou: the skeletal isotope chemistry of Eastern Arctic foragers. *Journal of Archaeological Science, 31*(1), 39-57.

Commission, I. W. (2018). Aboriginal Subsistence Whaling. Retrieved from https://iwc.int/aboriginal

Conconi, P., & Voon, T. (2016). EC-Seal Products: The Tension Between Public Morals and International Trade Agreements. *World Trade Review, 15*(2), 211-234.

Conrad, J. M. (1989). Bioeconomics and the Bowhead Whale. *Journal of Political Economy, 97*(4), 974-987.

Costanza, R., Cumberland, J. H., Daly, H., Goodland, R., Norgaard, R. B., Kubiszewski, I., & Franco, C. (2014). *An introduction to ecological economics.* : CRC Press.

Costanza, R., Wainger, L., Folke, C., & Mäler, K. G. (1993). Modeling complex ecological economic systems. *BioScience, 43*(8), 545-555.

Croll, D. A., Maron, J. L., Estes, J. A., Danner, E. M., & Byrd, G. V. (2005). Introduced Predators Transform Subarctic Islands from Grassland to Tundra. *Science, 307*, 3. doi:10.1126/science.1108485

Dalen, L., Fuglei, E., Hersteinsson, P., Kapel, C. M. O., Roth, J. D., Samelius, G., . . . Angerbjoern, A. (2005). Population History and Genetic Structure of a Circumpolar Species: the Arctic Fox. . *Biological Journal of the Linnean Society, 84*, 79-89. doi:doi:10.1111/j.1095-8312.2005.00415.x

Damas, D. (2002). *Arctic migrants/Arctic villagers: the transformation of Inuit settlement in the central Arctic.* Montreal: McGill-Queen's Press-MQUP.

Davis, L., Gallman, R., & Gleiter, K. (1997). *In Pursuit of Leviathan*. Chicago: University of Chicago Press.

Declercq, R. (2017). *World Market Transformation: Inside the German Fur Capital Leipzig, 1870-1939*. New York and London: Routledge.

Diamond, J. (2005). *Collapse: How Societies Choose to Fail or Succeed*: Viking Press.

Eide, A., & Flaaten, O. (1998). Bioeconomic multispecies models of the Barents Sea fisheries. In *Models for Multispecies Management* (pp. 141-172): Springer.
Eliasson, L., & Turnovsky, S. (2004). Renewable resources in an endogenously growing economy: balanced growth and transitional dynamics *Journal of Environmental Economics and Management, 48*(3), 31.
Fay, F. H., Eberhardt, L. E., Kelly, B. P., Burns, J. J., & Quakenbush, L. T. (1997). Status of the Pacific Walrus Population, 1950-1989. *Marine Mammal Science, 13*(4), 537-565.
Fisk, E. K., & Shand, R. T. (1970). The Early Stages of Development in a Primitive Economy: Evolution from Subsistence to Trade and Specialization. In C. R. Walton (Ed.), *Subsistence Agriculture and Economic Development*.
Freeman, M. M. R., Bogoslovskaya, L., Caulfield, R. A., Egede, I., Krupnik, I. I., & Stevenson, M. G. (1998). *Inuit, Whaling, and Sustainability*: Altamira Press.
Friesen, T. M. (1999). Resource structure, scalar stress, and the development of Inuit social organization. *World Archaeology, 31*(1), 21-37.
Gagnon, C. A., & Berteaux, D. (2009). Integrating Traditional Ecological Knowledge and Ecological Science: a Question of Scale. *Ecology and Society, 14*(2), 19.
Garrott, R. A., Eberhardt, L. E., & Hanson, W. C. (1983). Arctic Fox Den Identification and Characteristics in Northern Alaska. *Canadian Journal of Zoology, 61*(2), 423-426.
Gerth, N., Redman, P., Speakman, J., Jackshon, S., & Starck, J. M. (2010). Energy metabolism of Inuit sled dogs. *Journal of Comparative Physiology B, 180*(4), 577-589.
Gharajehdaghipour, T., Roth, J. D., Fafard, P. M., & Markham, J. H. (2016). Arctic Foxes as Ecosystem Engineers: Increased Soil Nutrients Lead to Increased Plant Productivity on Fox Dens. *Scientific Reports, 6*. doi:doi:10.1038/srep24020
Graugaard, N. D. (2018). Without seals, there are no Greenlanders. In *The Politics of Sustainability in the Arctic: Reconfiguring Identity, Space, and Time*.
Gross, A. (2010). *Background Document for Bowhead whale Balaena mysticetus*. Retrieved from
Hamilton, L. C., & Rasmussen, R. O. (2010). Population, Sex Rations and Development in Greenland. *Arctic, 63*(1), 43-52.
Hardin, G. (1968). The tragedy of the commons. *Science, 162*(3859), 1243-1248.
Higdon, J. (2008). *Commercial and subsistence harvests of bowhead whales (Balaena mysticetus) in eastern Canada and West Greenland*.
Higdon, J., & Ferguson, S. (2010). Past, present, and future for bowhead whales (Balaena mysticetus) in northwest Hudson Bay. In *A Little Less Arctic* (pp. 159-177): Springer.
Kaiser, B. A., & Parchomenko, A. (2018). Long Run Transitions in Resource-Based Inuit Communities. In N. Vestergaard, B. A. Kaiser, L. M. Fernandez, & J. Nymand-Larsen (Eds.), *Arctic Marine Resource Governance and Development* (pp. 89-114): Springer.
Kaiser, B. A., & Roumasset, J. (2014). Transitional Forces in a Resource Based Economy: Phases of Economic and Institutional Development in Hawaii. *Review of Economics and Institutions, 5*(2).
Kirch, P. V., & Sharp, W. D. (2005). Coral 230Th Dating of the Imposition of a Ritual Control Hierarchy in Precontact Hawaii. *307*(5706), 102-104. doi:10.1126/science.1105432 %J Science
Kruse, F. (2017). Catching up: the state and potential of historical catch data from Svalbard in the European Arctic. *Polar Record, 53*(5).

LeBlanc, J. A. (1996). Nutritional Needs In Cold And In High-Altitude Environments: Applications for Military Personnel in Field Operations. . In B. M. Marriott & S. J. Carlson (Eds.), *Cold Exposure, Appetite and Energy Balance*. Washington, DC: National Academies Press.
Lindgren, J. M. (1999). "Let Us Idealize Old Types of Manhood": The New Bedford Whaling Museum, 1903-1941. *The New England Quarterly, 72*(2), 163-206.
Lopez, R., Anriquez, G., & Gulati, S. (2007). Structural change and sustainable development. *Journal of Environmental Economics and Management, 53*(3), 15.
Lund, J. N., Josephson, E. A., Reeves, R. R., & Smith, T. D. *American Offshore Whaling Voyages: a database*. Retrieved from: http://www.nmdl.org
Marchani, E., Rogers, A., & O'Rourke, D. J. A. J. o. P. A. T. O. P. o. t. A. A. o. P. A. (2007). Brief communication: the Thule migration: rejecting population histories using computer simulation. *134*(2), 281-284.
May, R. M., Beddington, J. R., Clark, C., Holt, S. J., & Laws, R. M. (1979). Management of Multispecies Fisheries. *Science, 205*(July 20, 1979), 267-277.
McGhee, R. (2007). *The Last Imaginary Place: A Human History of the Arctic World*. Oxford: Oxford University Press.
Ménard, C., & Shirley, M. M. (Eds.). (2005). *Handbook of new institutional economics (Vol. 9)*. Dordrecht: Springer.
Mokyr, J. (2002). *The Gifts of Athena: Historical Origins of the Knowledge Economy*. Princeton: Princeton University Press.
Nedkvitne, A. (2019). *Norse Greenland: Viking Peasants in the Arctic*. London and New York: Routledge.
Nichols, P. (2009). *Final Voyage: A Story of Arctic Disaster and One Fateful Whaling Season*. New York: G.P. Putnam's Sons.
Nuttall, M. (2005). Inuit. In M. Nuttall (Ed.), *Encyclopedia of the Arctic*. London: Routledge.
Obbard, M. E., Jones, J. G., Newman, R., Booth, A., Satterthwaite, A. J., & Linscombe, G. (1999). Furbearer harvests in North America. In *Wild Furbearer Management and Conservation in North America*. Kingston, Ontario: Queen's University Press.
Pearce, T., Wright, H., Notaina, R., Kudlak, A., Smit, B., Ford, J. D., & Furgal, C. (2011). Transmission of Environmental Knowledge and Land Skills among Inuit Men in Ulukhaktok, Northwest Territories, Canada. *Human Ecology, 39*(271-288). doi:10.1007/s10745-011-9403-1
Raghavan, M., DeGiorgio, M., Albrechtsen, A., Moltke, I., Skoglund, P., Korneliussen, T. S., . . . Fitzhugh, W. (2014). The Genetic Prehistory of the New World Arctic. *Science, 345*(6200).
Rasic, J. T. (2016). Archaeological Evidence for Transport, Trade, and Exchange in the North American Arctic. In T. M. Friesen & O. K. Mason (Eds.), *The Oxford Handbook of the Prehistoric Arctic*. Oxford: Oxford University Press.
Rodseth, T. (2012). *Models for multispecies management*: Springer Science & Business Media.
Ross, G. (1974). Distribution, Migration and Depletion of Bowhead Whales in Hudson Bay, 1860 to 1915. *Arctic and Alpine Research, 6*(1), 85-98.
Scientists, I. U. o. C. (2018). *IUCN Red List*. Retrieved from: https://www.iucnredlist.org/
Southcott, C. (2010). History of Globalization in the Circumpolar World. In L. Heininen & C. Southcott (Eds.), *Globalization and the Circumpolar North*. Anchorage: University of Alaska Press.
Squires, D., & Vestergaard, N. (2013). Technical change in fisheries. *Marine Policy, 42*, 6.

Stewart, D. B., Higdon, J., Reeves, R. R., & Stewart, E. A. (2014). A catch history for Atlantic walruses (Odobenus rosmarus rosmarus) in the eastern Canadian Arctic. *NAMMCO Scientific Publications, 9*, 219-313.

Tejsen, A. V. S. (1977). The History of the Royal Greenland Trade Department. *Polar Record, 18*(116), 451-474.

Van den Bergh, J. C. (Ed.) (2002). *Handbook of environmental and resource economics*.: Edward Elgar Publishing.

Wein, E. E., Freeman, M. M. R., & Makus, J. C. (1996). Use of and Preference for Traditional Foods among the Belcher Island Inuit. *Arctic, 49*(3), 256-264.

Wenzel, G. W. (1996). Inuit sealing and subsistence managing after the EU sealskin ban. *Geographische Zeitschrift*, 130-142.

Wenzel, G. W. (2009). anadian Inuit subsistence and ecological instability —if the climate changes, must the Inuit? *Polar Research, 28*(1), 89-99. doi:10.1111/j.1751-8369.2009.00098.x

Woodby, D. A., & Botkin, D. B. (1993). Stock Sizes Prior to Commercial Whaling. In J. J. Burns, J. J. Montague, & C. J. Cowles (Eds.), *The Bowhead Whale*. Lawrence, KS: Society for Marine Mammology.

Appendix A: Visualization of the model in steps

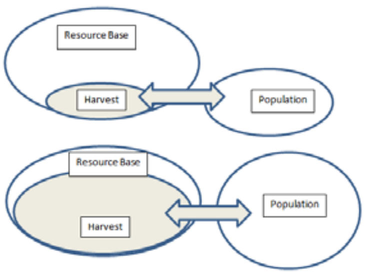


**Figure AA.1: Extensive Growth. The resource base is harvested to feed an endogenous human population in a predator-prey context. This can be replicated through migration to new areas, i.e. extensive growth. TEK is equally distributed across the population.**

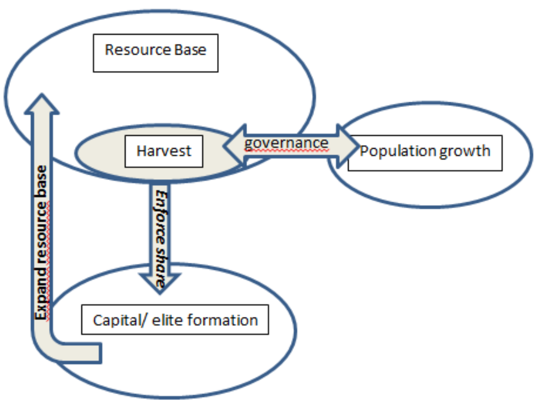


**Figure AA.2: Pre-trade Intensive growth. Capitalization requires management, which can expand the resource or exploit it. Specialized TEK develops that can expand the resource base's usefulness or the intensity of its use.**

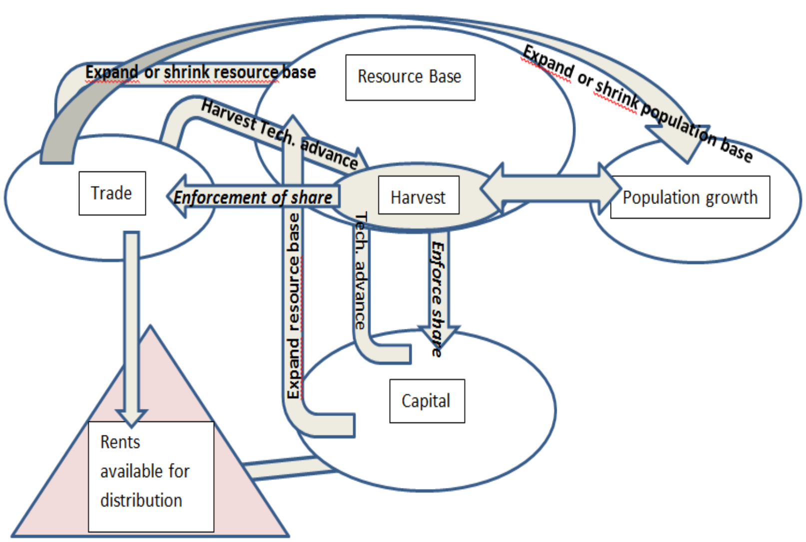


**Figure AA.3: Trade opens new opportunities and challenges.**

| Appendix B: Variable list | |
|---|---|
| Variable | Meaning<br>(All values at time *t*, time subscript suppressed) |
| *Control Variables* | |
| $\gamma$ | TEK dispersion factor (resource intensity coefficient) |
| S | Share of the resource to trade |
| $\varphi$ | Gross share of the resource to capital |
| *State variables* | |
| $n_1$ | Resource population |
| $n_2$ | Human population |
| $K_2$ | (Traditional Ecological Knowledge) Capital |
| *Valuation variables* | |
| $V_k$ | Unit value of capital |
| $P$ | Unit value of traded resource |
| $V$ | Unit value of consumption |
| $\lambda$ | Shadow value of resource base (ecosystem) |
| $\nu$ | Shadow value of (laborer) population |
| $\theta$ | Shadow value of TEK |
| *Cost variables* | |
| $w_c$ | Marginal cost of resource harvest |
| $w_\varphi$ | Marginal cost of governing share to capital |
| $w_s$ | Marginal cost of governing share to trade |
| $w_\gamma$ | Marginal cost of increasing ecosystem dispersion /resource intensity |
| *Technology, growth, depreciation and capacity variables* | |
| $c$ | Catchability coefficient |
| $\chi$ | Intraspecific competition coefficient |
| $A$ | Technological transformation coefficient for TEK creation |
| $\xi$ | Technological transformation parameter for TEK creation |
| $g_R$ | Intrinsic growth rate of resource base |
| $g_N$ | Intrinsic growth rate of human population |
| $K_1$ | Carrying capacity of the resource base (ecosystem) |
| $d$ | Death rate of human (laborer) population |
| $\delta$ | Depreciation of TEK (death rate of managerial elite) |
| *Other relevant expressions* | |
| $\varphi(1-s)$ | Net share of the resource to capital |
| $(1-s)(1-\varphi)$ | Share of the resource to consumption |

Appendix C: FOCs for fully specified Hamiltonian from Equations 1.1-1.4.

Recall the objective function:

$$Max\int_{t=0}^{\infty} e^{-rt}\left( V_{kt}K_{2t} + \begin{pmatrix} P_t s_t - w_{st}\left(\mathrm{N}\right)\mathrm{s}_t \\ +\left(1-s_t\right)\left(1-\varphi_t\right)V_t - w_{ct} - w_{\gamma t}\gamma\left(K_{2t}\right) \\ -w_{\varphi t}(\varphi_t,\mathrm{N})\varphi_t \end{pmatrix}\gamma\left(K_{2t}\right)c_t R_t N_t \right)dt$$

Which results in FOCs:

$$\dot{R} = \frac{\partial H}{\partial \lambda} = g_1 R\left(1-\frac{R}{K_1}\right) - \gamma\left(K_2\right)cRN \qquad \text{A.1}$$

$$\dot{N} = \frac{\partial H}{\partial \nu} = N\left( \underbrace{g_2\left(1-\varphi\right)\underbrace{\left(\underbrace{\gamma\left(K_2\right)cR\left(1-s\right)}_{consumed}\right)}_{consumed\ by\ laborers}}_{\text{intrinsic growth (laborers)}} - \underbrace{d}_{\text{mortality}} - \underbrace{\chi\left(K_2,\mathrm{N}\right)N}_{\substack{\text{intraspecific competition}(\chi>0) \\ or\ \text{cooperation } (\chi<0)}} \right) \qquad \text{A.2}$$

$$\dot{K}_2 = \frac{\partial H}{\partial \vartheta} = \underbrace{K_2}_{embodied\ \text{TEK}} * \underbrace{A^{\xi}\varphi\gamma\left(K_2\right)\left(1-s\right)cRN}_{\text{investment rate in TEK}} - \underbrace{\delta K_2}_{\text{depreciation of TEK (mortality)}} \qquad \text{A.3}$$

$$\frac{\partial H}{\partial c} = \gamma RN \qquad \text{A.4}$$

$$\left(\left(P-w_s\right)s + \left(V-\nu g_2\right)\left(1-s\right)\left(1-\varphi\right) - w_c - w_\gamma \gamma + \lambda - \varphi\left(K_2\left(\vartheta A^{\xi}\left(1-s\right)+w_\varphi\right)\right)\right) = 0$$

$$\frac{\partial H}{\partial \varphi} = \gamma cRN\left(-\left(V-\nu g_2\right)\left(1-s\right) - A^{\xi}\left(1-s\right)K_2\vartheta - w_\varphi - \varphi\frac{\partial w_\varphi}{\partial \varphi}\right) = 0 \qquad \text{A.5}$$

$$\frac{\partial H}{\partial s} = \gamma cRN\left(P - w_s - \left(V-\nu g_2\right)\left(1-\varphi\right) + A^{\xi}\vartheta\varphi K_2\right) = 0 \qquad \text{A.6}$$

$$\frac{\partial H}{\partial R} = r\lambda - \dot{\lambda} =$$

$$\gamma cN\left(\left(P-w_s\right)s + \left(1-s\right)\left(1-\varphi\right)\left(V-\nu g_2\right) + \varphi\left(A^{\xi}\left(1-s\right)K_2\vartheta\right) + \lambda - w_c - w_\gamma - \varphi w_\varphi\right) \qquad \text{A.7}$$

$$-\lambda\left(1-\frac{2R}{K_1}\right)g_1$$

$$\frac{\partial H}{\partial N} = r\nu - \dot{\nu} =$$

$$\gamma c R \begin{pmatrix} (P - w_s)s + (1-s)(1-\varphi)(V - \nu g_2) - \varphi\left(A^{\xi}(1-s)K_2\vartheta + w_\varphi\right) + \lambda - w_c - w_\gamma \\ -N\left(s\frac{\partial w_s}{\partial N} + \varphi\frac{\partial w_\varphi}{\partial N}\right) \end{pmatrix} \quad \text{A.8}$$

$$+\nu\left(d + N2\chi\right)$$

$$\frac{\partial H}{\partial K_2} = r\vartheta - \dot{\vartheta} =$$

$$V_K$$

$$+cRN \begin{pmatrix} \left(\vartheta A^{\xi}\varphi + \nu g_2(1-\varphi)\right)(1-s)\gamma \\ + \begin{pmatrix} s(P - w_s) + (1-s)\left((V - \nu g_2 K_2)(1-\varphi) + \varphi\vartheta A^{\xi}K_2\right) \\ +\lambda - w_c - w_\gamma - \gamma\frac{\partial w_\gamma}{\partial \gamma} \end{pmatrix} \frac{\partial \gamma}{\partial K_2} \end{pmatrix} \quad \text{A.9}$$

$$+\nu N^2\frac{\partial \chi}{\partial K_2} + \delta\vartheta$$

Simultaneous dynamic paths for the resource variables as functions of one another are obtained from combining equations A.7-A.9 with equations A.4-A.6 and their time derivatives, and shown here:

$$r - g_1\left(1 - \frac{2R}{K_1}\right) =$$

$$\frac{\gamma c N\left(-(P - w_s)(1-s) - V\left(1 - (1-s)(1-\varphi)\right)\right)}{-(P - w_s) + \varphi w_\varphi + w_c + \gamma w_\gamma} \quad \text{A.10}$$

$$+\frac{\left(-\left(\dot{P} - \dot{w}_s\right) + \dot{\varphi}w_\varphi + \dot{w}_c + \gamma\dot{w}_\gamma + \dot{\gamma}w_\gamma + \dot{K}_2\frac{\partial \gamma}{\partial K_2} + \dot{N}\left(\frac{\partial w_s}{\partial N} + \frac{\partial w_\varphi}{\partial N}\right) + \varphi\left(\dot{w}_\varphi + \dot{\varphi}\frac{\partial w_\varphi}{\partial \varphi}\right)\right)}{-(P - w_s) + \varphi w_\varphi + w_c + \gamma w_\gamma}$$

$$
\begin{aligned}
&\left(r-\left(d+N2\chi\right)\right)\\
&=\\
&-\frac{\gamma cRN\left(s\frac{\partial w_s}{\partial N}+\varphi\frac{\partial w_\varphi}{\partial N}\right)}{\left(\left(V-\left(P-w_s\right)\right)\left(1-s\right)+\varphi\left(w_\varphi+\varphi\frac{\partial w_\varphi}{\partial\varphi}\right)\right)}\\
&+\frac{1}{g_2\left(1-s\right)}\dot{s}\square\\
&\frac{\left(\left(P-w_s\right)\dot{s}+\dot{V}(1-s)\left(\dot{P}-\dot{w}_s-\dot{N}\right)+\dot{\varphi}\left(w_\varphi+\varphi\frac{\partial w_\varphi}{\partial\varphi}\right)-+\varphi\left(\dot{w}_\varphi+2\dot{\varphi}\frac{\partial w_\varphi}{\partial\varphi}+\varphi\dot{\varphi}\left(\frac{\partial w_\varphi}{\partial\varphi}+\frac{\partial^2 w_\varphi}{\partial\varphi^2}\right)\right)\right)}{\left(\left(V-\left(P-w_s\right)\right)\left(1-s\right)+\varphi\left(w_\varphi+\varphi\frac{\partial w_\varphi}{\partial\varphi}\right)\right)} \qquad \text{A.11}
\end{aligned}
$$

$$r-\delta-cRN\gamma A^{\xi}\varphi\left(1-s\right)=$$

$$A^{\xi}K_2\left(1-s\right)\frac{\left(V_K+\frac{V-\left(P-w_s\right)}{g_2}N^2\frac{\partial\chi}{\partial K_2}-cRN\gamma w_\gamma\frac{\partial\gamma}{\partial K_2}\right)}{\left(-\left(P-w_s\right)\left(1-s\right)-\left(w_\varphi+\varphi\frac{\partial w_\varphi}{\partial\varphi}\right)\left(1-\varphi\right)\right)}$$

$$+A^{\xi}K_2\varphi\frac{\frac{\left(w_\varphi+\varphi\frac{\partial w_\varphi}{\partial\varphi}\right)}{g_2}N^2\frac{\partial\chi}{\partial K_2}}{\left(-\left(P-w_s\right)\left(1-s\right)-\left(w_\varphi+\varphi\frac{\partial w_\varphi}{\partial\varphi}\right)\left(1-\varphi\right)\right)}$$

$$+A^{\xi}K_2\left(1-s\right)\frac{\left(\left(P-w_s\right)\dot{s}-\left(1-s\right)\left(\dot{P}-\dot{w}_s\right)-\dot{N}\frac{\partial w_s}{\partial N}\right)}{\left(-\left(P-w_s\right)\left(1-s\right)-\left(w_\varphi+\varphi\frac{\partial w_\varphi}{\partial\varphi}\right)\left(1-\varphi\right)\right)}$$

$$+\frac{\left(\frac{\dot{K}_2}{K_2}-\frac{\dot{s}}{\left(1-s\right)}\right)\left(w_\varphi+\left(1-\varphi\right)\varphi\frac{\partial w_\varphi}{\partial\varphi}\right)-\left(\dot{w}_\varphi+2\left(1-\varphi\right)\dot{\varphi}\frac{\partial w_\varphi}{\partial\varphi}+\left(1-\varphi\right)\varphi\left(\frac{\partial w_\varphi}{\partial\varphi}\dot{w}_\varphi+\dot{\varphi}\frac{\partial^2 w_\varphi}{\partial\varphi^2}\right)\right)}{\left(-\left(P-w_s\right)\left(1-s\right)-\left(w_\varphi+\varphi\frac{\partial w_\varphi}{\partial\varphi}\right)\left(1-\varphi\right)\right)}$$

A.12

**Appendix D: Carrying Capacity of the Composite Resource Base**

**Table AD.1**

| **Stock of the Composite Resource Base** | | | **Sensitivity Estimates** | | | |
|---|---|---|---|---|---|---|
| **Species** | **Carrying capacity (K1s) population (individuals)** | **Calories (Billions)** | **K1s-low** | **K1s-high** | **Calories (Billions): low** | **Calories (Billions): high** |
| Bowhead* | 23,500 | 9,118.00 | 12,000 | 35,000 | 3,171.90 | 16,975.00 |
| walrus | 841,000 | 4,759.18 | 300,000 | 1,000,000 | 1,157.51 | 7,716.75 |
| harp seal | 8,500,000 | 6,811.56 | 7,400,000 | 9,000,000 | 4,678.16 | 22,438.08 |
| ringed seal | 7,000,000 | 2,804.76 | 2,000,000 | 10,000,000 | 632.18 | 12,465.60 |
| bearded seal | 450,000 | 621.05 | 300,000 | 500,000 | 267.12 | 957.18 |
| hooded seal | 921,000 | 0.52 | 842,000 | 1,000,000 | 0.47 | 0.56 |
| Fisheries** | *110,000,000* | 11.00 | 69,800,000 | 279,200,000 | 6.98 | 27.92 |
| Arctic fox | 1,000,000 | 4.00 | 500,000 | 1,200,000 | 0.70 | 11.28 |
| Total Calories | | 24,130.07 | | | 9,915.03 | 60,592.37 |

*While beluga and narwhal are also consumed as part of the resource base, past and present population figures are very weak. I exclude these.

**Fisheries Carrying Capacity measured in biomass (kg) directly

| **Sources:** | **Population** |
|---|---|
| Bowhead | see Table 6 |
| walrus | see Table 7 |
| harp seal | Fisheries and Oceans Canada (2018b) |
| ringed seal | Fisheries and Oceans Canada (2018b) |
| bearded seal | Fisheries and Oceans Canada (2018b); NOAA Fisheries Service (2018) |
| hooded seal | Fisheries and Oceans Canada (2018b) |
| Fisheries | Zeller et al. (2011); Fisheries and Oceans Canada (2018a) |
| Arctic fox | Angerbjörn & Tannerfeldt (2014) |

*Caloric information from Agricultural Research Service USDA Food Composition Databases*

*Estimates of average blubber contents from Jakobsen (2016), Ryg et al (1990), Davies (2015)*

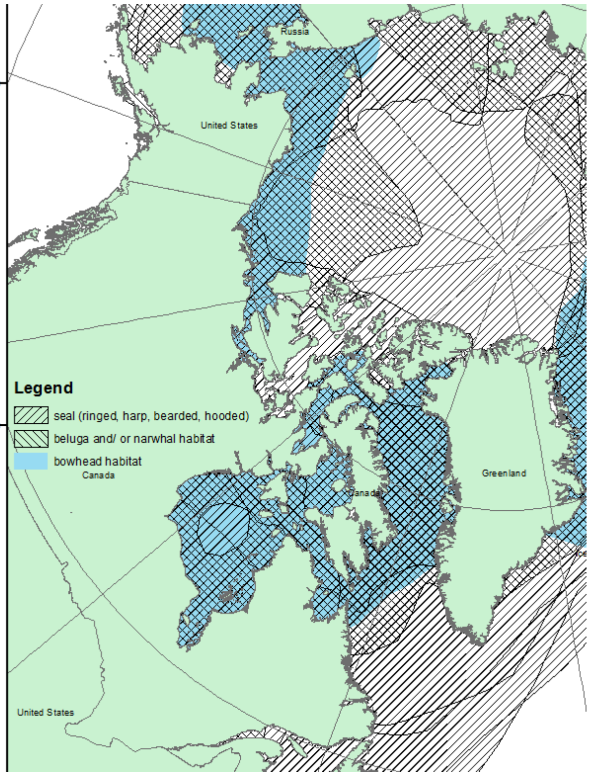


**Figure AD.1: Map of Arctic whale and seal habitats. Data source: (Scientists, 2018).**