

# Hudson Bay Ecosystem: Past, Present, and Future

C. Hoover

**Abstract** In order to gain insight into the dynamics of the Hudson Bay ecosystem as well as past and future states, an ecosystem model was created using a static Ecopath model to represent the present day ecosystem in Hudson Bay. Simulations of past and future ecosystem states were used to gain insight to key trophic linkages within the system, with focus on marine mammal populations. The past ecosystem was simulated by increasing ice algae and removing killer whales (*Orcinus orca*) from the system, which led to an increased biomass of all other groups within the model, excluding pelagic producers. Future states of Hudson Bay are presented in three scenarios representing various degrees of reported and predicted ecosystem changes including climate change and increased hunting pressure. All future scenarios show an overall decrease in species biomass, although some species are positively impacted by the changes in the system. Model simulations suggest bottom up forcing of ice algae is an important factor driving marine mammal biomass.

**Keywords** Hudson Bay • Ecosystem modelling • Ecopath with Ecosim • Food web • Climate change

## Introduction

Hudson Bay has been an important region to native cultures beginning with prehistoric Inuit roughly 4,000 years ago, and continuing up to the current Inuit and Cree communities which still inhabit the region today (Stewart and Lockhart 2005; Henri et al. this book). Aboriginal people have depended on the use of natural resources available to them, including birds, fish, plants, and marine mammals.

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Marine mammals generally found in the high Arctic latitudes are also found in relatively high abundances in Hudson Bay (Maxwell 1986), mostly due to the high Arctic climate being present at this lower latitude. Recently, marine mammals in the Arctic have been under increased stress caused by direct and indirect stressors such as; climate change, environmental contaminants, off-shore oil and gas activities, shipping, hunting, and commercial fisheries (Huntington 2009).

The average annual temperature in the Arctic has increased at a rate nearly double that of temperature increases in the rest of the world, and is expected to increase 4–7°C in the next 100 years (Arctic Climate Impact Assessment 2004). More specifically, climate models for Hudson Bay predict increases in annual precipitation, temperature from 3.9°C–4.5°C, and the length of the ice free period (Gagnon and Gough 2005). The combined effects of these changes to weather patterns impact ecosystems around the globe, with increased sensitivity in polar regions (Arctic Climate Impact Assessment 2004).

There are likely to be large scale changes within the ecosystem caused by increases in temperature. Perhaps most important will be changes to the extent and temporal dynamics of sea ice, which comprises the crux of the ecosystem. The extent of summer sea ice cover had decreased by 15–20% in the last 30 years in the Arctic, with the breakup of ice in Hudson Bay advancing at least 3 days per decade during 1971–2003 (Gough et al. 2004). As temperatures are predicted to continue increasing, ice cover in the Arctic is expected to nearly disappear later this century (Arctic Climate Impact Assessment 2004). This chapter addresses potential consequences these changes may have on the Hudson Bay ecosystem.

The Hudson Bay ecosystem, as it is referred to throughout this chapter, includes Hudson Bay and James Bay, and excludes Hudson Strait and Foxe Basin (Stewart and Barber this volume). Hudson and James Bays are rather shallow in contrast to the deeper and more dynamic Hudson Strait and Foxe Basin. Most of the marine species within Hudson Bay and James Bay complete their entire life cycle in this area, with the exception of some marine mammals.

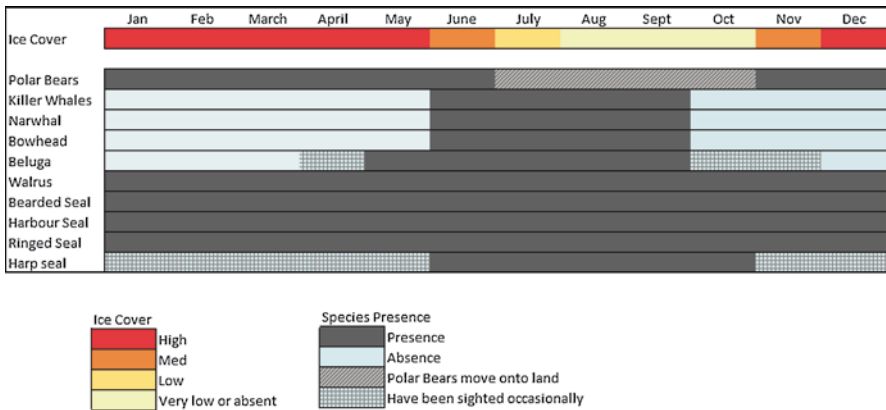
The annual sea ice cycle in Hudson Bay begins with freeze up by mid December, with the ice being the thickest from April to May and beginning to break up in June (Markham 1986; Stewart and Lockhart 2005). When the sea ice forms the phytoplankton and zooplankton species found within the water are frozen within the ice. Many species of phytoplankton and zooplankton have adapted to survive the winter frozen within the ice, and be returned to the water column the following summer to complete their life cycle (Horner et al. 1992). In the winter, this ice algae, which is concentrated at the ice–water interface, sustains the upper pelagic food web, which in turn provides nutrition for fish, seals, and polar bears (*Ursus maritimus*). Ice algae is an important source of energy, contributing up to 25–57% of annual primary production in some areas of Hudson Bay (Gosselin et al. 1997; Legendre et al. 1996).

Gammaridean amphipods are the dominant macrofauna feeding under ice on detritus that include ice algae, bacteria and crustacean remains (Poltermann 2001). The gammaridean amphipod is an important link between the lower trophic levels of sea ice based food webs and higher trophic level predators that include Arctic

cod (*Boreogadus saida*), ringed seals (*Pusa hispida*) and birds (Bradstreet and Cross 1982; Lonne and Gabrielsen 1992). In other polar ecosystems such as the Antarctic, ice algae is used throughout the winter by invertebrates such as Antarctic krill (*Euphausia superba*), which scrape the algae out of the ice as their main food source in winter (Marschall 1988, 1998; Nicol 2006). When the ice melts in the spring, the remaining algae are released into the water column, where it is available to copepods, krill, and other zooplankton. Portions of the Hudson Bay zooplankton community may also be able to consume the ice algae in late fall or early winter in much the same manner. Copepods are an abundant zooplankton in Hudson Bay, and an important food source to many species of fish, birds, and marine mammals (Estrada et al. 2008; Harvey et al. 2001). Copepod species located in Hudson Bay are able to utilize ice algae located at the ice-water interface before the annual phytoplankton bloom (Runge and Ingram 1987, 1991), which is believed to sustain the ecosystem in winter through to early spring (Freeman et al. 1982; Stewart and Lockhart 2005). In addition, copepods have adapted to aggregate under the melting sea ice in the spring to feed on the released algae (Conover et al. 1986; Runge and Ingram 1987, 1991), further demonstrating the importance of this trophic interaction.

The release of algae and some zooplankton species from the ice in the spring transport energy to the benthic food web which sustains molluscs, bearded seals (*Erignathus barbatus*), walrus (*Odobenus rosmarus*), and the Hudson Bay eider (*Somateria mollissima*) (Arctic Climate Impact Assessment 2004). Marine mammals in the Arctic have also adapted to survive with the sea ice cycle. Ringed seals build breeding dens on the sea ice under snow cover in the winter and early spring to protect their young from the elements (Chambellant this volume). Polar bears take advantage of this food source, by seeking out breeding dens and hunting young pups (Peacock et al. this volume). This winter/spring feeding period represents the majority of annual caloric intake for polar bears, building up their fat reserves for the summer months (Stirling and Derocher 1993). Sea ice provides walrus an alternative platform to land for pupping from April to June (NAMMCO 2005), and allows young calves a place to rest, decreasing travel distances and stress when they are learning to swim (Cooper et al. 2006). Bowhead whales (*Balaena mysticetus*) live most of their lives along the edge of the sea ice following it along their migration routes (Dyke et al. 1996), into Hudson Bay around June and back out in September (Stewart and Lockhart 2005). While the whales in the ecosystem generally migrate in and out every year, pinnipeds are year round inhabitants. Figure 1 shows a comparison of marine mammals and sea ice throughout the year to give an overview of which species might be most vulnerable to changes in sea ice.

Human residents of Hudson Bay have learned to utilize the numerous resources in order to survive in the region (Henri et al. this volume). Marine mammals have provided a food source to northern people since prehistoric times. In addition to food, Inuit continue to use the available natural resources to provide themselves with clothing and tools. Hunting also has a significant cultural importance to each community, as in the case of belugas, which brings the community together for a common goal and allows successful hunters to share their harvest with other families (Tyrrell 2007).



**Fig. 1** Freeze-up of ice begins in late November or early December and break-up of ice occurs from late June to late July (Gagnon and Gough 2005). Presence and sightings of marine mammals provided in Stewart and Lockhart (2005)

Currently narwhal, beluga, walrus, polar bears, seals, and bowhead whales are hunted along with select species of fish, invertebrates, and marine plants. Beluga, narwhal and bowhead are hunted for muktak (muktuk, maqtaq), the layer of skin and blubber, which is dried and eaten as a favorite food among many Inuit. Male narwhal possess an ivory tusk which is often made into carvings. Polar bears are hunted throughout Hudson Bay, mainly for their fur which is used to make clothing (Stewart and Lockhart 2005). Walrus are hunted for meat and their ivory tusks which are also used for carvings or sold whole (NAMMCO 2005). Historically walrus skins were used to make tents and ropes and their tusks were used to make harpoons (Stewart and Lockhart 2005). Seals provide a large amount of the protein consumed by native peoples, with their furs also being used for clothing.

Many Marine fish such as Arctic char (*Salvelinus alpinus*) and Greenland cod (*Gadus ogac*) are harvested for subsistence, but this harvest is currently unregulated, and no comprehensive stock assessments have been completed to estimate the amount harvested (Stewart and Lockhart 2005). Commercial fishery operations have been attempted; however, they were neither profitable nor productive. In some communities invertebrates such as green sea urchins (*Strongylocentrotus droebachiensis*) and blue mussels (*Mytilus edulis*) and marine plants are harvested for local consumption (Stewart and Lockhart 2005). The resources provided by this ecosystem continue to be a critical source for meeting the socio-economic needs to pursue the cultural integrity to the communities dependent on them.

An ecosystem modelling approach is used to gain insight into the dynamics of the Hudson Bay ecosystem at present as well as past and into the future. Here, a general representation of a sophisticated modelling exercise (detailed in Hoover et al. 2010) is presented. First a static model of the present day ecosystem in Hudson Bay was created. Then, based on knowledge of the past Hudson Bay conditions, an ecosystem model was simulated that incorporated the top down and bottom

up forcing. Lastly, three simulations of the future HB ecosystem were constructed to gain insight into key trophic linkages within the system, with focus on marine mammal populations.

## Methods

Model simulations representing the Hudson Bay ecosystem were created using the Ecopath with Ecosim suite of software (Buszowski et al. 2009; Christensen et al. 2007). This ecosystem modelling framework allows all species or species groups within the ecosystem to be connected through trophic linkages as defined by the user. Models are constructed in Ecopath, under a mass balance assumption to give a snapshot of the ecosystem in a particular time frame, and then projected through time using Ecosim, the dynamic portion of the modelling software. Full model structure, parameters, data sources, and trophic links for the Hudson Bay model are reported in Hoover et al. (2010). The three main analyses in this chapter are evaluations of the present, past and future states of the ecosystem.

### *Present*

The model constructed for the Hudson Bay ecosystem includes 40 functional groups representing all species or species groups found within the ecosystem. In this modelling exercise the current ecosystem state is represented as a static Ecopath model, and serves as a baseline to compare past and future ecosystem states. The model was constructed using published literature values, with all parameters available in Hoover et al. (2010). Because there are no comprehensive assessments of fish abundance or biomass for Hudson Bay the model was used to estimate the biomass of these groups. Biomass was estimated through a pedigree analysis, whereby parameters are ranked according to the credibility of their source, and then subjected to a Monte Carlo simulation to provide ranges of values. Due to the capabilities of Ecopath, each species group is required to have three of four required parameters (biomass, production, consumption, and ecotrophic efficiency), however, through the use of linear equations and trophic interactions the model can estimate one missing parameter per species group based on the inputs for other species groups. In essence there must be enough prey species to support a given biomass of predator with known growth and consumption rates. For full details on this please see Christensen et al. (2007). Unknown parameters are then estimated by solving for values which will fit into all sets of equations for the model, and repeated 1,000 times.

Hunting mortality was also incorporated into the model through the use of harvest statistics from 1989 to 1995 (DFO 1990, 1991, 1992, 1993, 1994, 1995, 1996, 1997, 1998, 1999; Stewart and Lockhart 2005). In addition, Harvest trends were used for future scenario C (increased hunting) in order to establish harvest mortalities.

## *Past*

Human populations in communities on the Nunavut portion of Hudson Bay (Arviat, Baker Lake, Chesterfield Inlet, Coral Harbor, Rankin Inlet, Repulse Bay, Sanikiluaq, Whale Cove) rose from nearly 4,700 in 1980 to over 9,000 in 2006 (Nunavut Bureau of Statistics 2008).<sup>1</sup> While this does not include population changes from the Nunavik or Ontario portions of Hudson Bay, the general trend has been high growth rates at most communities. While hunting methods may have improved through use of technology in recent years, targeted species and their use have not changed drastically from traditional use. Inuit still harvest animals for the same purposes as their ancestors; primarily as food and clothing, but also for trade and income.

Attempting to recreate the ecosystem around 1900 we note a few key differences. The bowhead whale population declined significantly from the late 1800s to the early 1900s due to commercial whaling and increased again towards the end of the twentieth century (Higdon and Ferguson this volume). In addition, ice cover throughout this time would have been higher than present levels, providing an increased source of ice algae. Finally, killer whales (*Orcinus orca*) would almost certainly be absent from the region, as their occurrence in Hudson Bay has only been documented since the 1950s according to a review of published literature and local knowledge (Higdon and Ferguson 2009).

In order to represent the past ecosystem (roughly 1900) the biomass of bowhead whales was increased (100%) along with ice associated algae (50%), while killer whales were removed from this simulation. Dynamic simulations were used to manipulate the killer whale, bowhead whale, and ice algae species groups. Forced biomass changes to these groups within the model simulation resulted in alterations to the rest of the ecosystem through trophic links, by altering prey available or predation on other species groups. Final values for simulations were taken as an average biomass for the last 5 years of the simulation, and were then compared to the baseline Ecopath model (or present day ecosystem) in Hoover et al. (2010) to give a relative increase or decrease.

## *Future*

In the past 20 years the extent of sea ice in the northern hemisphere has declined at a rate of about 3% per year (Parkinson et al. 1999). In Hudson Bay, analysis of ice trends from 1971 to 2003 show sea ice forming later in the fall and breaking up earlier in the spring (Gagnon and Gough 2005; Gough et al. 2004). Because the sea ice reflects solar radiation back into the atmosphere, its reduction caused by warming temperatures may increase solar radiation to the ocean, delaying the freeze up in successive years,

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<sup>1</sup>Prior to 1981 statistics for Nunavut were combine with Northwest Territories.

creating a positive feedback in the ecosystem (Gagnon and Gough 2005). This delay in sea ice formation would likely lead to a reduction in ice formed and an overall reduction of ice algae available to the food web. However, an increase in temperature is likely to increase primary production in the open water pelagic ecosystem in the form of spring blooms (Melnikov 2000). The switch in dominant phytoplankton from ice algae to pelagic phytoplankton blooms will most likely cause a restructuring of the food web, causing shifts in the abundance of zooplankton, benthos, and ultimately fish, birds, and marine mammals.

Direct effects to higher trophic level organisms are expected to occur. For example, bowhead whale migration routes follow the edge of the sea ice (Dyke et al. 1996) and changes to ice patterns may cause bowhead whales to shift their migration routes into this ecosystem (Ferguson et al. in review). This may potentially alter feeding opportunities at decreased ice edges, or allow for greater exposure to predation by killer whales. Earlier spring break-up of sea ice together with a change in snow trends can cause ringed seal dens to collapse through melting, exposing the young pups to harsh climates thereby reducing pup survival in western Hudson Bay (Ferguson et al. 2005). The breakdown of dens also exposes pups to polar bears, making them easier to find, thus further increasing the population mortality (Stirling and Parkinson 2006). The feeding season of the polar bear has been altered in the last 35 years (Stirling and Parkinson 2006), as a decreasing ice season impairs their ability to hunt and build energy stores needed to survive the ice free period (Peacock et al. this volume). This may also lead to declining body condition, lower reproductive rates, and decreased survival of polar bear cubs (Stirling and Derocher 1993). Whereas bears used to remain on the ice for much of the spring and summer they now travel closer to settlements in order to seek out food, thus increasing their interactions with humans (Stirling and Parkinson 2006).

Perhaps the most immediate effect of sea ice loss to the food web will be a change in primary production. By removing or altering the physical structure of sea ice, the flow of energy and carbon from ice algae to higher trophic level organisms will be reduced spatially and temporally thus limiting energy and nutrient transfer to higher trophic levels.

Considering the increases in human population over the last 30 years, it is likely that there will be continued growth. This will put additional pressure on resources that will include marine mammals if future generations continue to hunt and follow traditional lifestyles. Although estimates of current harvest levels are not always accurate due to difficulty in obtaining harvest levels for all species, it is assumed that increasing populations will consume more resources than the present day.

Based on predicted changes described above the following three scenarios were used for the future simulations of Hudson Bay ecosystem:

- (A) A 50% reduction in sea ice algae biomass
- (B) A 50% reduction in sea ice algae biomass, a 50% reduction in copepod biomass, a 50% reduction in polar bear biomass, a 25% reduction in ringed seal biomass, a 25% reduction in bird biomass, and a 25% increase in killer whale biomass
- (C) Scenario B plus a 100% increase in hunting-based mortality

The increased hunting scenario incorporates the same ecological changes as future scenario B plus a doubling of harvest rates on all marine mammals to account for a future doubling in human population size. Again, the biomass of specified species groups was altered to identify the consequent changes to the ecosystem through trophic linkages. For scenario C catches were forced to double their current rate. Average biomass for the last 5 years of the simulation was used as the final value, and compared to present day values.

## Results and Discussion

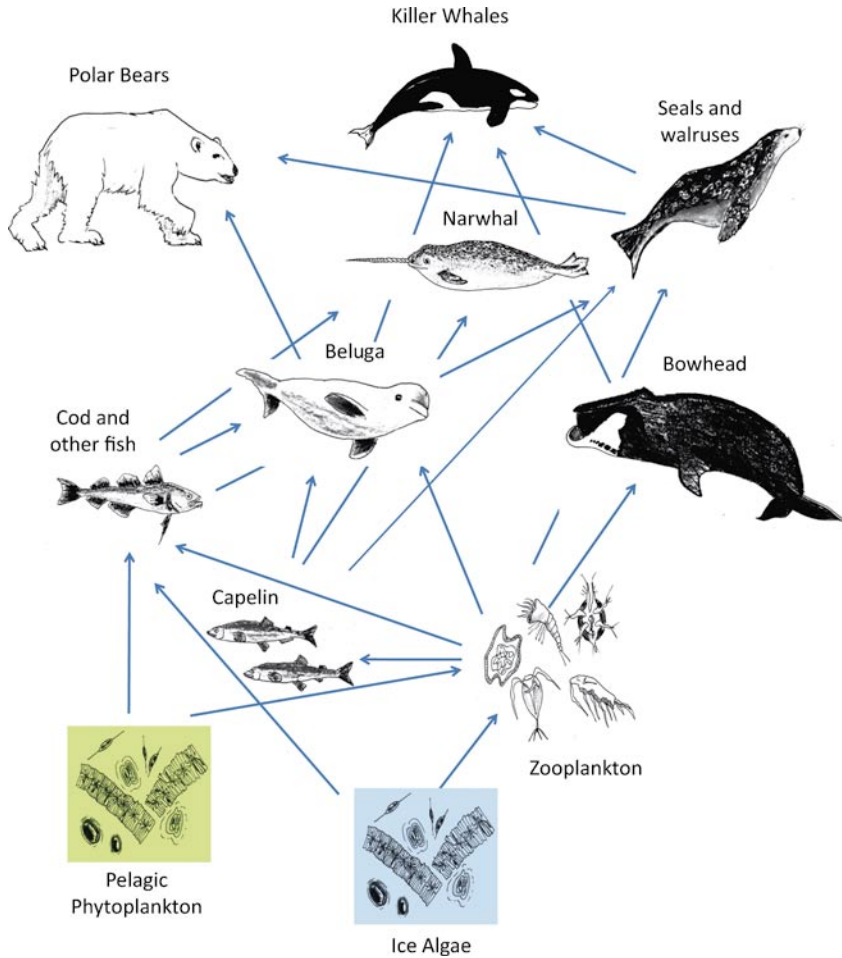
Within each section the results for each scenario are presented and discussed. Figures 2, 4, and 5 illustrate the Hudson Bay food web for present, past, and future scenarios respectively while Fig. 6 presents mean changes in past and future biomass relative to present biomass. Key species were selected for figures leaving birds, benthos, and some individual species groups missing from the figures. These groups were included in the full model, but excluded for graphical purposes due to the large number of species groups in the model.

### *Present Ecosystem*

Figure 2 shows the simplified Hudson Bay ecosystem, the trophic links as they are believed to exist today, and serves as a reference point for past and future ecosystem states. In this food web both sea ice algae and pelagic phytoplankton represent the autotrophic primary producers, whereby seasonality and ice cover largely determines prevalence of each one. Copepods being the dominant zooplankton, provide an essential link between producers and consumers, fuelling fish and other zooplankton species. Capelin are an important forage fish to marine mammals and birds which annually migrate through the regional. A full list of species found within the ecosystem is available from Stewart and Lockhart (2005), along with the modeled functional groups of species Hoover et al. (2010).

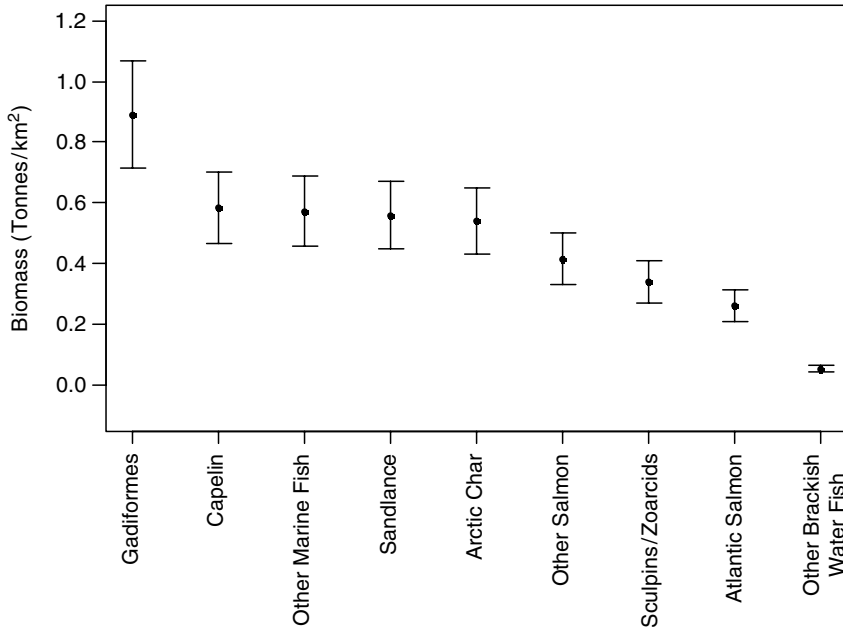
While there are no surveys of fish to estimate abundance, as little is known (Stewart and Lockhart 2005), pedigree ranking for Hudson Bay as provided in Hoover (2008), and Monte Carlo simulations were used to estimate fish biomass. By constraining the ecosystem through the abundance of predators and the amount of production available at the base of the food web, a biomass estimate of all fish groups is provided in Fig. 3. In comparison to other ecosystems, the biomass of fish in Hudson Bay is relatively low, as one might expect considering unsuccessful attempts of commercial operations within the ecosystem. For example on average Hudson Bay has 2.4 tonnes per km<sup>2</sup> for all fish species, which as expected is substantially less than reported values for other ecosystems: Ionian Sea 6.43 tonnes per km<sup>2</sup> (Piroddi 2008), or the Antarctic peninsula 4.32 tonnes per km<sup>2</sup>





**Fig. 2** Principal trophic linkages in the present day food web in Hudson Bay. Images courtesy of Megan Bailey

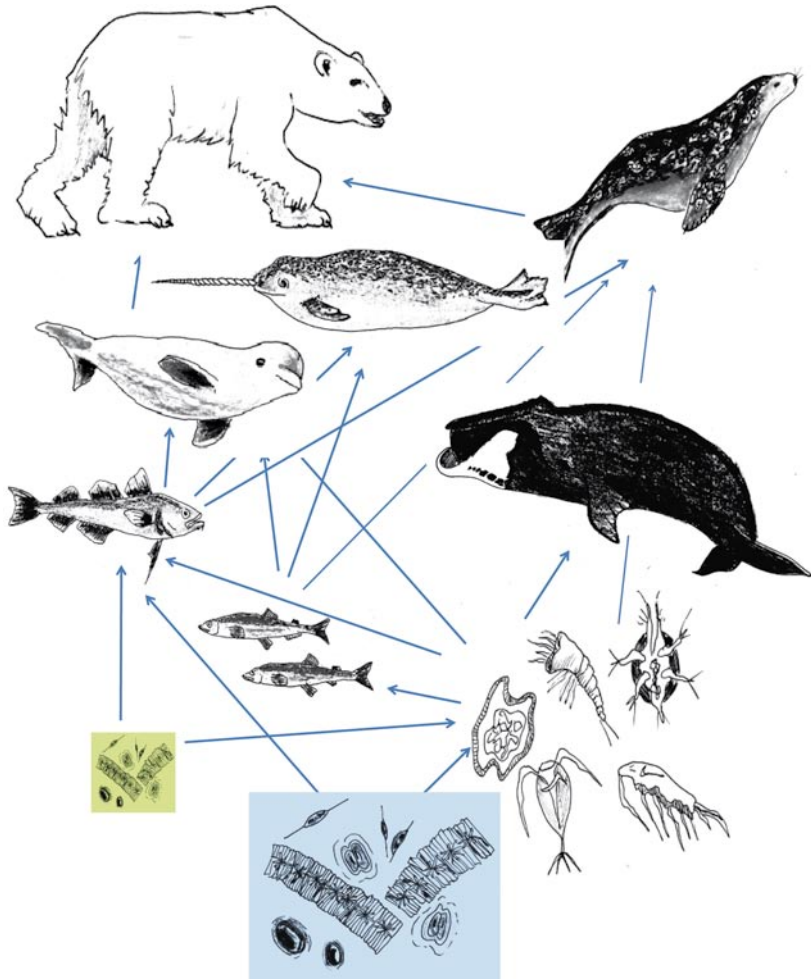
(Hoover and Pitcher 2009). Thus, these preliminary estimates appear to be within a reasonable range given comparisons for other ecosystems. Because these values are contingent upon the ability of the ecosystem to produce enough prey, the needs of predators, and the food web links, they are sensitive to the input parameters of other modeled groups. For example an underestimate of marine mammal biomass will require less prey (fish biomass) within the model, and vice versa. Overestimates of primary production can cause overestimates in higher trophic level organisms. However, input parameters for primary producers and marine mammals were obtained from published literature and subjected to Monte Carlo routines to estimate errors.



**Fig. 3** Biomass estimates for fish species in the Hudson Bay ecosystem. Monte Carlo simulations provide 95% confidence Limits based on pedigree ranking in Hoover 2008. Refer to Appendix for a full list of species within each fish grouping

## Past

For this simulation, ice associated algae were increased by 50% of their present day biomass, in order to account for the increased sea ice in the past. In addition, bowhead whale abundance was doubled to represent the highest abundance in the late 1800s (Higdon and Ferguson this volume). These changes, combined with the removal of killer whales as top predators resulted in an increase in biomass in every species group within the model, with the exception of pelagic primary production (Fig. 4). The decrease in pelagic primary production is due to the limitation of nutrients through the detritus functional group, which become increasingly scarce as they are utilized by the ice algae groups which is forced to increase in this simulation. Zooplankton groups increased the most, up to 50% of their present day biomass, most likely attributed to the increased ice algae, an important food source. This was propagated up the food web, where fish biomasses increased from 20% to 30% depending on the species group. Seal biomass increased 30% on average with harbor seals (*Phoca vitulina*) increasing the most at 38%, and harp seals (*Phoca groenlandica*) increasing the least at 28%. In addition, polar bears and beluga (*Delphinapterus leucas*) groups both increased 38%, while narwhal (*Monodon monoceros*) biomass increased by 59%. It should be noted that such



**Fig. 4** Representation of Hudson Bay Ecosystem in the past accounting for increased ice-algae, increased bowhead whales, and the absence of killer whales. Images courtesy of Megan Bailey

large increases are not necessarily believed to be representative of the past ecosystem, but rather to identify what sort of shifts may have occurred when comparing the past and present ecosystems.

Due to multiple perturbations to the system, it is difficult to identify which factors are having significant effects on each species group. The removal of killer whales from the system should allow certain marine mammal species (narwhal, bowhead, beluga, walrus, and seals) to increase their biomass through reduced predation (note this does occur to all species except bowhead which were forced to increase in this simulation). However, the increased ice algae impacted the ecosystem through bottom-up trophic interactions which is likely responsible for the increases

in zooplankton and fish biomass. It is difficult to tease out which interactions are affected most by each change within the ecosystem unless multiple combinations of perturbations are run. Nevertheless, insight into the future ecosystem scenarios may shed some light on these processes.

## ***Future***

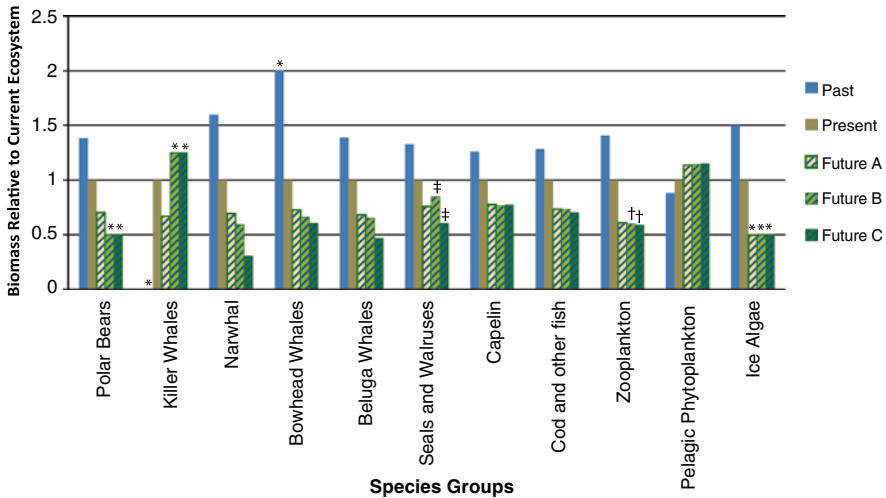
Killer whale abundance in Hudson Bay has increased exponentially as they migrate into Hudson Bay to take advantage of the populations of other marine mammals as food (Ferguson et al. this volume). Their appearance in the last 50 years has been linked to decreasing sea ice, which has allowed them easier access to the food resources in Hudson Bay (Higdon and Ferguson 2009). Heavy sea ice cover prevents the narwhal from overwintering in Hudson Bay. However, a decrease in ice might allow them to remain in Hudson Bay longer each year, and possibly overwinter, although other factors such as available prey and exposure to predators will also influence movements (Laidre and Heide-Jørgensen 2005).

Three future ecosystem simulations were performed (Fig. 5). For Scenario A, the 50% reduction in ice-algae biomass was based on a 30% reduction already observed and the possibility of sea ice disappearing in the next century (Arctic Climate Impact Assessment 2004). This scenario was created to represent an estimate of food web changes, assuming a loss of sea ice would result in a loss of ice algae and lead to cascading ecosystem changes. The resulting impacts to the ecosystem show averages of 30% decrease in biomass for all marine mammals, 25% decrease in biomass for all fish, 40% decrease for zooplankton biomass, 20% decrease in benthic biomass, and a 15% increase in pelagic primary production. Increases in biomass to species groups in the past ecosystem scenario were larger than the decreases under future scenario A, indicating that ice algae is important, but not the sole reason for biomass increases in the past simulation.

For scenario B, the same changes to the ecosystem were observed with the exception of a further decrease to narwhal, caused by the increased killer whales (Fig. 6). Seal biomass did increase slightly, about 8%, from scenario A, likely due to the further decrease in their predator, the polar bear. Some of the largest changes between scenarios A and B were due to species groups being forced. For example polar bears only declined by 29% of present values under scenario A, but were forced to a 50% reduction in scenario B indicating that although sea ice may be contributing to their decline through alterations of the food web, other interactions are also resulting in substantial declines.

As expected, scenario C shows the greatest declines in biomass for many species groups, in particular the hunted marine mammal species. Results show there are further reductions of marine mammal biomasses, with bowhead, harbor seals, and ringed seals having minor further reductions to population; decreases less than 10% of future scenario B (Fig. 6). The likely reason for this is current harvest rates for these species (bowhead, harbor seals, and ringed seals) are low relative to their population





**Fig. 6** Comparison of select species group biomass for the following scenarios; past, future A, future B, and future C presented as a percentage increase or decrease from the present day biomass. For species groups representing multiple species within the full model are averaged within the figure. Species groups where biomass was forced in specific scenario are indicated (\*). Groups with multiple species, where only one component was forced are marked as ‡ (for ringed seals within “Seals and Walrus”) and † (for copepods within “Zooplankton”)

sizes, thus even a doubling of harvest does not significantly alter the population biomass in the model. Narwhal were the most severely impacted marine mammal species with an overall decline of 75% from present day biomass, a further decline of 45% from scenario B demonstrating this species’ sensitivity to increased mortality rates.

Scenarios of past, present, and future ecosystems of Hudson Bay reveal the importance of ice-algae to the food web dynamics and as an important driver of ecosystem productivity. The increase in ice algae for the past ecosystem shows an increase across nearly every species group within the model, while reductions of ice algae for future scenario A showed declines in nearly all species groups. Future scenarios incorporating increased mortality through increased predation (i.e. killer whales) or hunting activities, generally did not have as strong of an impact on the higher trophic level species as did the reductions in ice algae. These results indicate the ecosystem is sensitive to bottom-up forcing.

While models can provide an overview of changes to a system, and assess perturbations, it is unlikely that any of these scenarios will truly reflect the future state of the Hudson Bay ecosystem. By altering species or species groups within the model, the impact to the food web can be studied, thereby identifying new research directions and contributing to the understanding of the food web dynamics. The author does not assume to have an all-inclusive knowledge of the system, but rather intends to provide some insight to ecosystem links that are important to user

groups, researchers, and management, by using the data and research available at present.

The approaches taken here did not account for physiological effects of warming, loss of habitat, or feedback loops resulting from sea ice reduction and increased temperature. In addition, alterations to the food web and replacement of trophic levels by invasive species are likely to occur in Hudson Bay and throughout the Arctic as temperatures increase. These considerations are important components when assessing ecosystem responses to stressors such as climate change and hunting. However, these were not accounted for within the current modelling framework, and should be considered in additional studies as they would provide value to the overall understanding of the ecosystem.

There have been few ecosystem studies in Hudson Bay, so understanding the changes in other systems in relation to climate change will help establish plausible futures for Hudson Bay. The scenarios presented show a linear progression of the ecosystem under predetermined varying conditions. However, longer term studies of populations over hundreds of years have shown cyclical patterns of abundance through ecosystem changes. For example a 2000 year time series of anchovy and sardine abundance in the Pacific Ocean reveals changes in the abundance of these species, portraying a waxing and waning pattern (Hayword 1997). These regime shifts, or oscillations in biomass, have allowed either the anchovy or the sardine to increase its abundance in the ecosystem, only to be replaced by the other through the next regime shift. The consequences are observed in higher trophic level species, such as seabirds which primarily consume anchovies (Chavez et al. 2003), as their abundance also fluctuates in accordance with the regime shifts. In the Bering Sea, regime shifts are thought to be caused by atmospheric oscillations which drive changes in the physical environment such as wind, ocean upwelling, and extent of freshwater plumes; these were hypothesized to result in the population crash of Stellar seal lions (*Eumetopias jubatus*) (Benson and Trites 2002). These changes in the physical system have affected species at various trophic levels beginning with the spatio-temporal changes in primary production, to a shift in forage fish species and to ones that may not have had the nutritional content to sustain top predators such as Stellar sea lion (Trites and Donnelly 2003; Trites et al. 2007).

In light of information on regime shifts, and given the ability of ecosystems to switch between dominant species, multiple different futures for Hudson Bay are possible. The ecosystems studied with known shifts are quite “data rich” when compared to systems like Hudson Bay. Sediment cores from southern Hudson Bay roughly 8000 BP indicate ostracods were the dominant zooplankton (Bilodeau et al. 1990). Perhaps, the reduction of sea ice and increases in seasonal pelagic phytoplankton have allowed for reorganization of dominant zooplankton, and in the future will allow different zooplankton species and forage fish to dominate the ecosystem. Warming of Hudson Strait and Foxe Basin may allow new species to cross these currently colder waters, and enter Hudson Bay. Invasive species may well lead to the local extirpation of some species, and will likely result in restructuring of the food web. Adaptations in diet are not exclusive to marine organisms, as humans will likely be forced to adjust their diets to the resources available to them.

As shown through bottom-up forcing of the Hudson Bay ecosystem model, and supported by bottom-up induced regime shifts, the effects of climate change on the physical environment easily cascade to have far reaching consequences throughout the entire ecosystem.

## Summary

Assessment of the current ecosystem structure in conjunction with past and future scenarios indicate the Hudson Bay ecosystem is sensitive to bottom-up forcing, specifically from ice algae. Future simulations show a decrease in ice algae affecting nearly every species group within the Hudson Bay ecosystem model. While controlling hunting mortality may be an important factor to managing marine mammal stocks, decreases in ice algae appear to have a more significant effect on most species of marine mammals. Future work on specific effects of sea ice loss in relation to individual species is imperative to improve modelling techniques as well as an overall understanding of the Hudson Bay ecosystem and climate change.

## Appendix

Fish groupings for the Hudson Bay ecosystem modeled after Stewart and Lockhart (2005). Under the classification, only species found within Hudson and James Bays which spend at least part of their life in areas where they would be available to marine mammals were included. In Stewart and Lockhart (2005) these are classified as; Marine, Brackish, Estuarine, and some Diadromous.

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<b>Atlantic Salmon</b>	
Atlantic salmon	<i>Salmo salar</i>
<b>Arctic Char</b>	
Arctic Char	<i>Salvelinus alpinus</i>
<b>Capelin</b>	
Capeli	<i>Mallotus villosus</i>
<b>Gadiformes</b>	
Arctic cod	<i>Boreogadus saida</i>
Greenland cod	<i>Gadus ogac</i>
Polar cod	<i>Arctogadus glacialis</i>
<b>Other Brackish Water Fish</b>	
Arctic shanny	<i>Stichaeus punctatus</i>
Canadian plaice	<i>Hippoglossoides platessoides</i>
Slender eelblenny	<i>Lumpenus fabricii</i>
<b>Other Marine Fish</b>	
Alligator poacher	<i>Leptagonus decagonus</i>

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(continued)



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Atlantic alligatorfish	<i>Ulcina olriki</i>
Atlantic Herring	<i>Clupea harengus</i>
Atlantic spiny lumpsucker	<i>Eumicrotremus spinosus</i>
Banded gunnel	<i>Pholis fasciata</i>
Daubed shanny	<i>Leptoclinius maculatus</i>
Dusky snailfish	<i>Liparis gibbus</i>
Fourline snakeblenny	<i>Eumesogrammus praecisus</i>
Gelatinous snailfish	<i>Liparis fabricii</i>
Kelp snailfish	<i>Liparis tunicatus</i>
Leatherfin lumpsucker	<i>Eumicrotremus derjugini</i>
Lumpfish	<i>Cyclopterus lumpus</i>
Sea tadpole	<i>Careproctus reinhardti</i>
Stout eelblenny	<i>Anisarchus medius</i>
<b>Other Salmon</b>	
Arctic Char	<i>Salvelinus alpinus</i>
Brook trout	<i>Salvelinus fontinalis</i>
Lake cisco	<i>Coregonus artedi</i>
Lake whitefish	<i>Coregonus clupeaformis</i>
Round whitefish	<i>Prosopium cylindraceum</i>
<b>Sandlance</b>	
Northern sand lance	<i>Ammodytes dubius</i>
Stout sand lance	<i>Ammodytes hexapterus</i>
<b>Sculpins/Zoarcids</b>	
Arctic eelpout	<i>Lycodes reticulatus</i>
Arctic sculpin	<i>Myoxocephalus scorpiodes</i>
Arctic staghorn	<i>Gymnocanthus tricuspis</i>
Fish doctor	<i>Gymnelus viridis</i>
Fourhorn sculpin	<i>Myoxocephalus quadricornis</i>
Moustache sculpin	<i>Triglops murrayi</i>
Pale eelpout	<i>Lycodes pallidus</i>
Ribbed sculpin	<i>Triglops pingelli</i>
Shorthorn sculpin	<i>Myoxocephalus scorpius</i>
Spatulate sculpin	<i>Icelus spatula</i>
Twohorn sculpin	<i>Icelus bicornis</i>

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