**Do hyperabundant Arctic-nesting geese pose a problem for
sympatric species?**

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1 **Do hyperabundant Arctic-nesting geese pose a problem for sympatric species?**

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Abstract

Arctic-breeding geese are at record high population levels and are causing significant changes to some of their breeding and staging habitats. These changes could influence sympatric wildlife, but the nature and strength of these effects are unknown. Here, we review the interactions between geese and sympatric species and propose future research that could help to fill important knowledge gaps. We suggest that geese may be indirectly affecting other species through changes to nesting habitat, prey availability, and predator-prey interactions. Many ground-nesting Arctic birds prefer vegetated wet tundra habitats that offer concealed nest sites; areas also heavily used by breeding and staging geese. Where goose foraging exceeds the capacity of the plants to regenerate, habitats have shorter graminoids and more exposed substrate, potentially reducing the availability of concealed nest sites for other birds. Studies have documented local reductions in the abundance of these concealed-nesting species, such as shorebirds. Despite the nutrient enrichment contributed by goose feces, habitats heavily altered by geese have also been shown to host a reduced diversity and abundance of some invertebrate groups. In contrast, generalist predators show positive functional and numerical responses to the presence of breeding geese. Therefore, the risk of predation for alternative or incidental prey (e.g., lemmings or small bird nests) is likely elevated within or near breeding colonies. Studies have demonstrated a reduced abundance of small mammals in areas heavily used by geese, but it is unknown whether this is related to shared predators or habitat alteration. Sympatric wildlife could be further affected through higher stress-levels, altered body condition, or other physiological effects, but there is currently no evidence to demonstrate such impacts. Few studies have explored the potential effects of

geese at larger spatial scales, but we suggest that hyperabundant geese could result in regional declines in the abundance and diversity of shorebirds and passerines. We recommend coordinated studies across multiple regions to quantify nesting habitat, arthropod communities, and predator-prey interactions in response to nearby goose colonies. To align with current multispecies approaches to conservation, adequate knowledge of the potential effects of hyperabundant goose populations on other wildlife should be a priority.

Key words: overabundant, geese, shorebirds, predator-prey, nest site, habitat change

Draft

In many areas of Arctic and sub-Arctic North America, hyperabundant populations of northern-breeding geese (primarily Lesser Snow, *Chen caerulescens caerulescens* and Ross' Geese, *Chen rossii*, hereafter collectively referred to as 'light geese') are altering their breeding and staging habitat through overgrazing and grubbing, with a substantial influence on ecosystem structure and function (Batt et al. 1997). The effects of geese on tundra vegetation have been well described, especially for sub-Arctic areas around Hudson and James Bay, Canada (Cargill and Jefferies 1984; Abraham et al. 2005b; Jefferies et al. 2006). In contrast, we know very little about the mechanisms whereby geese might be affecting other wildlife and the significance of these effects, if any. Here, we outline the potential effects both positive and negative that light goose populations may be having on northern ecosystems with a particular focus on the wildlife communities that inhabit them. We examine the empirical evidence for and mechanisms underlying interactions between geese and sympatric wildlife communities, and make recommendations for studies to fill the most pressing knowledge gaps.

Opposing Trends and Overlapping Distributions

Goose Population Increases

Several species of geese are widely distributed across the North American Arctic and many have experienced dramatic population growth (Leafloor et al. 2012; Kerbes et al. 2014). Midcontinent Lesser Snow and Ross' Geese in particular have increased in abundance. An approximately fourfold increase in abundance between the 1950s and 2000s is suggested by mid-winter counts of these two populations (Abraham et al. 2005a). At La Pérouse Bay, a goose colony situated approximately 30 km east of

Churchill, Manitoba (Fig. 1), numbers of Lesser Snow Geese have grown over 10-fold from approximately 5,600 adults in 1972 to 58,700 in 1997 (Kerbes et al. 2006) and then to 83,600 individuals in 2006 (Kerbes et al. 2014). Within the Central Canadian Arctic, the Ross' and Lesser Snow Goose colonies were estimated to hold nearly 2.8 million nesting individuals in 2005-2006, in comparison to 44,300 individuals 40 years earlier (Kerbes et al. 2014). The most recent photographic surveys across all known breeding colonies in the Central and Eastern Arctic suggest over 6.1 million breeding Snow and Ross' Geese, a 40% increase over the estimates from the same areas in 1997-1998 (Kerbes et al. 2014). Estimates of the total population (breeders and non-breeders) suggest even larger population growth; recent band-recovery models indicate that the total adult population for Midcontinent Lesser Snow Geese may exceed 15 million individuals (Alisauskas et al. 2011).

Regardless of the method of abundance estimation, the Lesser Snow Goose population is well above the stated management objective of 1.5 million individuals for the Midcontinent population, as are most other populations of Snow and Ross' Geese (NAWMP 2012). The Western Arctic and Midcontinent populations of Lesser Snow Goose, the Greater Snow Goose (*Chen caerulescens atlanticus*), and Ross' Goose are all formally designated as overabundant in Canada (e.g., CWSWC 2014).

These dramatic increases in light goose populations are largely attributed to changes in agricultural practices that have led to rises in food subsidies at goose overwintering areas and along migration routes (Batt 1997; Jefferies et al. 2004). Increases in the area cultivated and the intensity of agriculture, along with a shift by light geese away from their traditional coastal habitats and towards agricultural habitats has led

to increased overwinter survival (Batt 1997; Abraham et al. 2005a). The patterns and causes of population increases in light geese are reviewed in detail in Batt (1997) and Abraham et al. (2005a).

Population Changes for Other Birds

Arctic habitats used by geese are also widely used by other bird species including other waterfowl, passerines, and shorebirds. In contrast to geese, several populations from these groups have experienced declines. Several Arctic-nesting landbird populations (Downes et al. 2011) and in some areas, the number of nesting pairs of Black Brant (*Branta bernicla nigricans*; Wilson 2010) have declined. Many populations of Arctic-breeding shorebirds have declined dramatically (Zöckler et al. 2013) with a disproportionate number of declines occurring among those breeding in the eastern and central Arctic regions of North America (Bart et al. 2007; Andres et al. 2012; Smith et al. 2012). These disproportionate declines prompted our interest in the potential for geese to influence other declining populations of Arctic-breeding birds. Currently, any links between these population declines and abundant geese have yet to be made.

Overarching causes for many Arctic-breeding bird population declines remain unknown, but threats such as habitat loss and climate change are often suggested to be the most significant contributors to these declines (Thomas et al. 2006; Downes et al. 2011; North American Bird Conservation Initiative 2012). Sparse human settlement in the North American Arctic and sub-Arctic suggests that anthropogenic habitat loss is at most a local issue, but little is known about the larger-scale threats that many species face on their Arctic breeding grounds. Hyperabundant populations of geese and the associated

habitat change have been suggested as possible threats to other northern wildlife populations (Batt et al. 1997), particularly for those groups whose habitat requirements overlap with those of geese.

Habitat and Scale

Goose-induced Habitat Alteration

Hyperabundant populations of light geese have significantly altered their staging and breeding areas at several Arctic and sub-Arctic locations (Batt 1997; Kotanen and Jefferies 1997; Abraham et al. 2005b, 2012). At sub-Arctic staging and breeding areas in the Hudson Bay Lowlands, early season grubbing of belowground roots and rhizomes reduces the stored energy of forage plants, impeding regrowth and long-term plant viability (Srivastava and Jefferies 1996; Batt 1997; Jefferies et al. 2002; Jefferies et al. 2004). In wetland or saltmarsh communities, heavy grazing can result in higher local soil temperature and salinity (Iacobelli and Jefferies 1991), which may impede re-vegetation and in some cases lead to an alternate habitat state of exposed sediment (Srivastava and Jefferies 1996). Re-vegetation after significant alteration by geese has been documented suggesting vegetation may rebound in some cases and alteration may not always be permanent (Kotanen and Jefferies 1997). The influences of heavy grazing pressure mean that almost all intertidal marshes in the Hudson Bay Lowlands have been severely altered in recent decades, along with large areas of supratidal marsh and other coastal habitats (Abraham et al. 2012).

Evidence of significant habitat change exists from other Arctic and sub-Arctic locations outside of the Hudson Bay lowlands as well. On Southampton Island, large-

scale changes in land cover types from grass/sedge meadows to exposed sediment and peat have been attributed to grazing by geese (Fontaine and Mallory 2011; Brown 2014). The most recent estimates suggest nearly 1 million breeding light geese on the island, a 5-fold increase since the 1970s (Kerbes et al. 2014).

At Karrak Lake in the Central Arctic, breeding light geese have altered habitats substantially through foraging and nest building (Alisauskas et al. 2006). Lowland areas within the breeding colony have seen “virtually complete removal of graminoid plants”, with a total reduction in plant biomass from 380g/m² outside the colony to 83g/m² within (Samelius and Alisauskas 2009). Large areas of peat have been exposed and species richness and diversity of vegetation reduced where there is a long history of occupancy by light geese (Didiuk and Ferguson 2005; Alisauskas et al. 2006). However, research throughout the Queen Maud Gulf Migratory Bird Sanctuary (61,765km²) that surrounds Karrak Lake suggests that there are large areas of apparently suitable wet sedge meadows unoccupied and therefore unaffected by geese to the south and west of the known breeding colonies.

On Bylot Island, exclosure plots, which removed grazing by Greater Snow Geese for 5 years, had 67% greater biomass than those exclosed for only a single season, with the community composition shifting towards a greater relative abundance of *Eriophorum*, a preferred goose forage species (Gauthier et al. 2006). Goose effects on the habitats of Bylot Island are considered to be minor in comparison to other sites such as the Hudson Bay Lowlands (Gauthier et al. 2006), and overall primary productivity at that high Arctic site is in fact increasing, a likely result of climatic warming (Gauthier et al. 2013). Similarly, on Banks Island, in the Western Arctic, local habitat alteration may be

occurring in response to the increasing goose populations but minimal large-scale changes have been reported (Hines et al. 2010).

Range, Habitat Use, and the Scale of Possible Interactions

Habitat loss or alteration is one key mechanism whereby northern-breeding and staging geese might influence sympatric species. To crudely estimate the potential geographic scope of light goose impacts, we conducted a series of large-scale spatial analyses using range and vegetation maps. Light geese are broadly distributed across the North American Arctic (Fig. 1). To describe their habitat use at a coarse spatial resolution, we overlaid the maximum extent of mapped breeding areas on the Circumpolar Arctic Vegetation Map (CAVM Team 2003) using ArcGIS 9.3 (ESRI 2009). The CAVM defines blocks of habitat at a scale of tens of square kilometers, based on an aggregation of finer-scale data from the Advanced Very High Resolution Radiometer (AVHRR). The maximum extent of mapped colonies of Lesser Snow Geese (data from Kerbes et al. 2014 and Canadian Wildlife Service unpublished) is 11,516 km², which includes 3,800km² of colonies in sub-Arctic areas of South Hudson Bay, outside of the areas mapped by the CAVM. Similarly detailed spatial data for the breeding distribution of Greater Snow and Ross' Geese are not available. For colonies within the areas mapped in CAVM, 5,686 km² (74%) of area used is classified as wetlands. This represents approximately 3% of the total area classified as wetlands in the North American Arctic or 0.2% of the land area overall, suggesting a small spatial extent of Lesser Snow Geese in the Arctic. However, goose-related habitat alteration may extend well beyond the polygons defining nesting areas. For instance, at Wapusk National Park,

Manitoba, goose-related habitat alteration through shoot-pulling has been documented up to 19 km inland from a coastal goose colony, although the intensity of this change decreased significantly with distance from colony (Rockwell et al. unpublished). The overlap of colonies and wetlands may therefore underestimate the spatial extent of the influence of geese.

Published range maps provide an indication of all areas where light geese are known to occur regularly, which is an upper limit to the possible extent of their influence on habitats. We overlaid the best available range maps for light geese on the CAVM to describe breeding-season habitat use for the population as a whole. The published summer range for Snow and Ross' Geese covers approximately 26% of the North American Arctic, including large fractions of the areas classified as wetlands and moist, vegetated uplands (Fig. 2). Range maps are crude and areas vary greatly in goose density and thus the potential degree of influence, if any, that geese have on the ecosystem. We emphasize that this likely represents the uppermost limit of goose effects and the potential for interactions between geese in the Arctic during the breeding season and sympatric species.

Taxa that are highly reliant on wetlands during the breeding season such as many shorebirds (Brown et al. 2007) may be particularly susceptible to interactions with northern goose populations. For instance, wetlands (preferred by geese) contain more than 2.5 times the densities of shorebirds found in other habitats (Bart and Smith 2012). Applying the habitat specific densities of shorebirds observed during Arctic PRISM (Program for Regional and International Shorebird Monitoring; Bart et al. 2002) surveys across the range of light geese suggests that up to 30% of all Arctic-nesting shorebirds

may interact with geese during the breeding season. The extent of this overlap may be species-specific since there is significant variation in range and habitat requirements of different shorebird species. This estimate still provides a valid upper limit for the potential of goose-shorebird interactions.

Light geese also potentially influence their northern staging grounds, and key stopover areas where many migrating species congregate might serve to expose even larger fractions of populations to the potential effects of hyperabundant geese. Saltmarsh habitats along much of the Hudson and James Bay coasts are considered significantly altered as a result of intensive foraging by geese (Abraham et al. 2012). These coastlines include several important bird stopover sites, such as the Nelson River estuary where tracking data suggest that 68% of the population of the endangered *rufa* Red Knot (*Calidris canutus rufa*) stops to forage during northward migration (McKellar et al. 2015).

These spatial analyses, while crude, suggest that there is at least the potential for hyperabundant light geese to have population-level impacts on other species. However, refined spatial data for the geographic distributions of both geese and other species are needed to better estimate the potential scope of the issue. Moreover, an improved understanding of the demographic impacts of the interactions between sympatric species and various densities of breeding and non-breeding light geese is needed in order to translate spatial overlap into population consequences. There are many mechanisms whereby geese might affect sympatric species, varying widely in terms of potential demographic outcomes. At present, few of these pathways are sufficiently well understood to estimate the severity of effects on other wildlife populations.

Potential Mechanisms of Goose Interactions with Sympatric Species

Heavy foraging pressure has the potential to have cascading effects on ecosystem structure and function (e.g., McShea and Rappole 2000; Martin et al. 2010; Rae et al. 2014). In temperate regions, over-browsing by deer can reduce the abundance and diversity of browse-layer nesting birds (Allombert et al. 2005a; Gill and Fuller 2007; Martin et al. 2011), as well as the abundance and species richness of browse-layer invertebrates (Miyashita et al. 2004; Allombert et al. 2005b; Martin et al. 2010), important bird prey items. In agricultural landscapes, graminoid-nesting birds may be less abundant and productive in harvested grasslands compared to natural grasslands (Dale et al. 1997). In Arctic ecosystems, goose-induced alteration of habitat could be having similar effects on other species' nest sites and prey availability through various indirect interactions (Fig. 3). Furthermore, light geese could be indirectly influencing the reproductive success of sympatric species through interactions with their shared predators. Predators are often attracted to locally abundant prey and this access to prey can also lead to increased reproductive output of predators, in both cases elevating the risk of predation on other species (Bui et al. 2010; McKinnon et al. 2013a).

The combined effects of changes in available habitat, prey availability, and predation pressure on sympatric species through indirect interactions with light geese are largely unstudied. Below, we examine empirical evidence for and the mechanisms behind goose and sympatric species interactions in Arctic and sub-Arctic areas and attempt to comment on the degree to which light goose populations might affect other wildlife populations.

Habitat and Community Composition

Light goose colonies could have significant impacts on local community composition and abundance. Over a 25 year period, in the vicinity of a light goose colony at La Pérouse Bay, Rockwell et al. (2003) documented a 77% decline in Savannah Sparrow (*Passerculus sandwichensis*) nesting density along with decreases of between 46% and 94% of the proportion of shrub class vegetation. Since shrub-dominated areas are the primary nesting habitat used by this species, Rockwell et al. (2003) attributed this decline in nest density to the decline in shrub cover.

Nearby, at Cape Churchill, Sammler et al. (2008) estimated non-geese avifauna population abundance in the vicinity of a colony in 1984, 1999, and 2000. Over the course of the study, changes in local bird density were inconsistent and no direct correlations between changes in vegetation and population size were identified (Sammler et al. 2008). At the scale of the study site (48 km²), Semipalmated Sandpiper (*Calidris pusilla*) and Savannah Sparrow densities increased over the three time periods, while Pacific Loon (*Gavia pacifica*), Arctic Tern (*Sterna paradisaea*), Pectoral Sandpiper (*Calidris melanotos*), and Red-necked Phalarope (*Phalaropus lobatus*) abundances decreased.

At the scale of a habitat patch, songbirds and shorebirds were greater than two and three times more abundant, respectively, in sedge meadow habitats than in similar habitat that had been disturbed by goose grubbing (Sammler et al. 2008). Many of the species recorded have small territories and so Sammler et al. (2008) suggested that larger-scale goose habitat alteration would be required to generate detectable population-level

changes in other birds.

Similar conclusions were made near a Lesser Snow Goose colony on Banks Island in the Western Arctic. Latour et al. (2010) conducted transects at various distances from the colony and found only weak increases in the nesting density of shorebirds and passerines with increasing distance. However, due to the small area of habitat affected and the low shorebird nesting densities, Latour et al. (2010) suggested that impacts on shorebird and passerine populations may be hard to detect or not significant.

Small mammals also have the potential to be affected by geese. At Karrak Lake, in the Queen Maud Gulf Bird Sanctuary, Nunavut, Samelius and Alisauskas (2009) documented a negative relationship between small mammal abundance and nesting geese. Specifically, in lowland areas, average abundance (captures per 100 trap-nights) of small mammals (Red-backed Voles, *Clethrionomys rutilus*; Collared Lemmings, *Dicrostonyx torquatus*; Brown Lemmings, *Lemmus sibiricus*) was 0.2 within the goose colony and 2.6 outside of the colony. This 13-fold difference was suggested as being primarily driven by the drastic differences in average aboveground plant biomass between within (83 g/m²) and outside (380 g/m²) the colony which small mammals require for food and cover.

Predator communities may benefit from goose colonies, particularly generalist predators that prey on goose eggs and goslings. In the Western Hudson Bay region, Herring Gull (*Larus smithsonianus*) populations near a goose colony multiplied fourfold over 15 years of increasing goose abundance (Sammler et al. 2008). At a Glaucous Gull (*Larus hyperboreus*) colony in the Queen Maud Gulf, goose eggs and goslings made up a significant proportion of gull chick diet, which may contribute to higher growth,

particularly for large broods (Samelius and Alisauskas 1999).

There is also evidence demonstrating that Arctic Fox (*Vulpes lagopus*) populations benefit from goose colonies. On Bylot Island, during years when lemming populations are low, the probability of Arctic Fox dens being used for successful fox reproduction decreased by 71% for every 10 km traveled from the nearest goose colony (Giroux et al. 2012) suggesting a high reliance of foxes on geese for prey, at least during periods of low small mammal abundance. At Karrak Lake, Samelius et al. (2011) demonstrated that geese and their eggs subsidize fox diets such that regional fox populations are larger than could be supported by small mammals alone.

Species at even higher trophic levels may also be benefiting from goose colonies. In some areas, Polar Bear (*Ursus maritimus*) diets are changing as a result of earlier sea-ice breakup, which reduces their ability to hunt for marine mammals (Derocher et al. 2004) and leads to bears coming ashore while geese are still incubating eggs. Some studies have noted increased predation of Snow Goose nests by Polar Bears (Rockwell et al. 2009; Smith et al. 2010), and where they are available, eggs have been suggested as a substitute food resource for bears (Gormezano and Rockwell 2015). Along the Cape Churchill Peninsula, Gormezano and Rockwell (2013) found that bird parts were found in 29% of Polar Bear scats and 43.1% of these were Snow Geese. As sea-ice breakup continues to arrive earlier, increased Polar Bear presence around goose colonies is possible, and reduced goose population growth has even been suggested as a consequence of increased predation by these large predators (Rockwell et al. 2011).

Overall, the results of these studies suggest that light geese have the potential to negatively influence passerine and shorebird communities as well as small mammals, at

least at local or regional scales. At sites where habitat alteration from grubbing and grazing is pronounced, the adverse effects on shorebird, passerine, and small mammal densities and diversity are also pronounced. Conversely, predator communities appear to benefit from goose colonies, with greater densities and reproductive output in the vicinity of breeding geese.

Impacts of Shared Nest Predators

Predation is the primary cause of nest failure for many tundra-nesting birds (Smith et al. 2007; Liebezeit et al. 2009; McKinnon and Bêty 2009, Hoover et al. 2010) and therefore changes in predator numbers and predation rates could have strong effects on reproductive success and ultimately population status. In most Arctic locations, Arctic Foxes are believed to be the dominant nest predator, however, Glaucous and Herring Gulls, Parasitic (*Stercorarius parasiticus*) and Long-tailed Jaegers (*S. longicaudus*), and Common Ravens (*Corvus corax*) among others, may also contribute to predation (Bêty et al. 2001; McKinnon and Bêty 2009, Hoover et al. 2010).

Predators in the Arctic capitalize on scarce or unpredictable resources by showing functional and numerical responses in the presence of abundant prey. On Bylot Island, Arctic Fox activity can be up to three times higher in areas with high goose nesting densities (>10 goose nests per hectare) than areas with no goose nests (McKinnon et al. 2013a). This locally elevated predator abundance can lead to an increased risk of predation for other prey.

At La Pérouse Bay, Iles et al. (2013) attributed the long-term negative correlation between Common Eider (*Somateria mollissima*) nest success and Snow Goose abundance

to goose-subsidized aerial predator communities. In Alaska, predators are more abundant near human infrastructure (that provides food, perching and denning sites) and these subsidized predator populations reduce the nest survival of passerines and some shorebird species breeding nearby (Leibezeit et al. 2009). Modeling exercises performed by Leibezeit et al. (2009) indicate that the probability of a passerine nest surviving to fledging increased by ~50% as the distance to human infrastructure used by predators increased by ~5 km.

The effect of increased predation risk on nesting birds may be most significant when other prey items are scarce. For example, McKinnon et al. (2014) found that the risk of predation on artificial shorebird nests was inversely related to lemming abundance and during lemming crash years, the risk of predation was especially high in the presence of breeding geese (a 17% increase in predation risk with an increase from 0 to 1 goose nests per hectare, equating to a 600% increase in the risk of predation in areas with a high goose nest density of 12 per hectare; McKinnon et al. 2013a).

Arctic Foxes are efficient predators, occupy large home ranges (between 10 and 50 km²; Prestrud 1992; Anthony 1997), and when food availability is high, can have litters of up to 22 pups (Tannerfeldt and Angerbjörn 1998). These life history characteristics can translate into high densities of foxes and therefore, large areas with a high risk of predation, which could impact their prey items' reproductive success.

While these studies suggest that the presence of geese leads to an elevated risk of predation for sympatric-nesting species, there is evidence that some species might instead benefit from predator satiation or 'swamping'. Baldwin et al. (2011) found a ~15% greater likelihood of survival of Cackling Goose (*Branta hutchinsii*) nests within a Ross'

goose colony compared to nests outside the colony, which was attributed to predator swamping. However, this benefit was offset by interspecific conflicts in areas with high densities of nesting geese, which can lower overall nest success because of reduced nest attentiveness (Baldwin et al. 2011).

The interactions occurring between predators, primary prey and incidental prey in these northern ecosystems are complex (Bêty et al. 2001; Bêty et al. 2002; Legagneux et al. 2012). In some instances, species could benefit from predator satiation near goose colonies, however, these positive effects may be negated by aggressive interactions with geese. In general however, it appears that the risk of nest predation for other species breeding near geese is elevated, because of the greater abundance of generalist predators. The effects of elevated predator abundance could be compounded by a reduction in the availability of nest sites with tall vegetation and high concealment, for those species relying on concealment to avoid predation. The true scale and severity of these impacts, and what they might mean for the populations of sympatric species, remain largely unknown.

Impacts on Sympatric Species' Habitat Availability

Many Arctic shorebirds and passerines prefer lowland habitat types for feeding and nesting (e.g., Bart and Smith 2012; Saalfeld et al. 2013), and some species select highly concealed nest sites in graminoid-dominated habitat types (Boal and Anderson 2005; Smith et al. 2007; Walpole et al. 2008). In contrast, some highly vigilant species such as the Black-bellied Plover (*Pluvialis squatarola*) or Ruddy Turnstone (*Arenaria interpres*) actively select nest sites with an open view of the surroundings (Smith et al. 2007).

Heavy grazing by geese can remove significant quantities of above-ground vegetation. In some areas, Snow Geese can consume up to 60% of the standing crop in wet meadows (Gauthier et al. 2006) and as much as 80% of the net above ground primary production (NAPP) of marsh habitat (Cargill and Jefferies 1984). At large-scales, these changes could result in significantly lower densities of many cover-nesting shorebird species.

At East Bay on Southampton Island, Red Phalaropes (*Phalaropus fulicarius*) and White-rumped Sandpipers (*Calidris fuscicollis*) nest in sedge meadow and scrub willow habitats, selecting nests in dense vegetation that provides significantly greater concealment than at random sites (14 and 23% vs. 8% for random sites; Smith et al. 2007). Similarly, in Wapusk National Park east of Churchill, Manitoba, Lapland Longspurs (*Calcarius lapponicus*) select nest sites with an average 67% lateral concealment (Boal and Anderson 2005). On the north slope of Alaska, King Eiders (*Somateria spectabilis*) select nest sites with >16% concealment by willow to protect against mammalian and aerial predators (Bentzen et al. 2009). These species may avoid nesting in areas that lack suitably concealed nest sites, or may be more susceptible to predation when forced to select inadequately concealed sites. Liebezeit et al. (2009) estimated that tundra-nesting passerines experienced a 7.4% increase in nest predation given a 10% decrease in nest concealment (Liebezeit et al. 2009). However, some species select open nest sites with an unobstructed view of the surroundings, such as the Semipalmated (*Charadrius semipalmatus*) and Black-bellied Plover (Smith et al. 2007). For these open-nesting, vigilant species goose-induced habitat alteration could lead to an

increase in the abundance of suitable nest sites, or at worst be neutral from the perspective of availability of suitable nest sites.

Changes in Invertebrate Communities

Invertebrate communities may also be influenced by goose-induced habitat alteration, or by the changes in the communities of the insectivores that prey on them. Sherfy and Kirkpatrick (2003) examined the effects of goose foraging on moist soil invertebrate communities using goose-exlosures at a temperate overwintering area, the Prime Hook National Wildlife Refuge bordering Delaware Bay, Delaware. Here, invertebrate abundance was significantly lower in areas subjected to foraging geese, with chironomid and coleoptera abundance particularly low in these areas. Taxa richness and weighted Simpson's diversity indices (D_w) were also lower outside of the exclosures (5.6 vs. 6.5 taxa/sample, $D_w = 0.8$ vs. 0.9). These effects were attributed to indirect consumption of invertebrates by the grazing geese in open areas and greater vegetation cover in goose-excluded areas.

Our understanding of the effects of goose-induced habitat change on invertebrates in northern ecosystems is limited to two studies conducted at La Pérouse Bay, Manitoba. Both suggest that goose foraging has impacts on aquatic and terrestrial invertebrate community composition and abundance. Invertebrate communities in ponds in goose-grubbed areas were comprised of a single chironomid species, whereas, in intact sites, the communities consisted of five chironomid species representing four genera (Milakovic et al. 2001). Average chironomid abundance at goose-impacted sites was two times lower, but biomass was not affected as a result of the larger-bodied chironomid species that

inhabited the ponds in degraded areas (Milakovic et al. 2001).

Similar trends were found for terrestrial invertebrates. In goose-influenced habitat, spider abundance and species richness was nearly five and two times lower, respectively, than in intact habitat (Milakovic and Jefferies 2003) and average beetle abundance was up to seven times lower in degraded habitat (Milakovic and Jefferies 2003). In both studies, the differences in invertebrate communities were attributed to higher salinity (Milakovic et al. 2001), lower moisture and lower vegetation cover in degraded areas, reducing the suitability of the habitat for arthropods (Milakovic and Jefferies 2003).

Light geese may be contributing nutrients to northern wetlands by way of fecal deposition, which could increase the productivity of the generally oligotrophic aquatic systems of the Arctic. At a reservoir in Pennsylvania, Snow Geese contributed 93% of the phosphorus and 44% of the nitrogen loads (Olson et al. 2005). In Arctic wetlands, aquatic invertebrate abundance is higher in nutrient rich ponds (Brodersen and Anderson 2002; Luoto et al. 2016). Although benefits of goose-induced nutrient input into Arctic wetlands have been suggested (Alisauskas and Kellet 2014) there is limited evidence to suggest either positive or negative impacts on invertebrate communities. Research on the topic is currently underway on Southampton Island, Nunavut (H. Mariash, *unpublished*).

If breeding and staging light geese are affecting invertebrate communities, populations of insectivorous birds could also be affected. During the breeding season, birds require an abundance of suitable invertebrate prey items to maximize their reproductive output and survival (Martin 1987). Insectivorous chicks can develop poorly when arthropod availability is low (Schekkerman et al. 1998; Schekkerman et al. 2003;

McKinnon et al. 2013b). In extreme cases, Red Knot (*Calidris canutus*) chicks can lose up to 8g (>7%) of their body weight in one day when temperatures are low (Scheckerman et al. 2003), and chick starvation can be high when primary prey abundance is low (Pearce-Higgins and Yalden 2004).

Variability in invertebrate prey abundance and chick survival could also translate into changes in habitat use. European Golden-plover (*Pluvialis apricaria*) chicks often use habitats that yield the highest abundance of invertebrates at the time (Pearce-Higgins and Yalden 2004). Lapland Longspurs and White-crowned Sparrows (*Zonotrichia leucophrys*) in Alaska also select nest sites based on vegetation and prey availability likely to increase the survival of their chicks (Boelman et al. 2015).

The susceptibility of species to any changes arising from goose-induced alterations of invertebrate communities depends on the invertebrates selected for prey. Black-bellied and Semipalmated Plovers, as well as Ruddy Turnstones typically feed on terrestrial invertebrates such as spiders and beetles, but will also take chironomids (Paulson 1995; Nettleship 2000; Nol and Blanken 2014). Goose-induced reductions in the abundance of these prey items could translate into reduced chick growth or increased chick mortality for these species. Conversely, species such as Red Phalaropes that rely on chironomid larvae and other aquatic invertebrates more heavily (Tracy et al. 2002) may be less, or even positively, affected. Dietary preferences and flexibility could play an important role in determining the influence of goose-related changes in invertebrate communities on foraging insectivores.

Sub-lethal, Carry-over, and Direct Effects

Goose-induced modifications of Arctic and sub-Arctic environments could also have further, sub-lethal consequences for sympatric species. For migrating species, reductions in food availability might result in carry-over effects felt during migration or over subsequent years. Such effects may manifest through later departure dates (Cooper et al. 2015), increased stopover times, and ultimately lower survival during migration or non-breeding.

An increase in the need for anti-predator behaviours or increased vigilance due to augmented predator communities could reduce the amount of time spent foraging and may lead to chronic stress of individuals (Lima 2009). For example, Song Sparrows (*Melospiza melodia*) exposed to frequent experimental nest predation lay fewer eggs per clutch, have more clutches overall, and are in poorer overall condition than birds not exposed to constant perceived risk of predation (Travers et al. 2010). Likewise, when experimentally exposed to a high risk of predation while in food limiting environments, Song Sparrows experienced chronic stress and produced smaller and lower quality offspring (Clinchy et al. 2004). When the risk is particularly high, birds may abandon their nests or forego breeding altogether (Spaans et al. 1998; Lima 2009). Over long periods, these sublethal effects on individuals could have population-level consequences.

Sympatric-nesting species could also be experiencing direct effects of goose presence. Foraging geese may flush other incubating birds from their nests at more frequent intervals causing the eggs or chicks to be left without incubation for longer periods. Disturbances to brooding birds can result in increased thermal and energetic stress (Weston and Elgar 2005), or elevated risk of nest predation because of increased activity around the nest (Smith et al. 2012).

509

510 Future Considerations and Conservation Implications

511 Light geese are widely distributed across the Arctic and sub-Arctic, and interact with a
512 diverse array of species throughout their range. However, studies of the effects of light
513 geese on habitat are limited to a few sites and studies of goose impacts on other species
514 more limited still. Furthermore, our understanding of the issue may be influenced by
515 publication biases whereby only significant negative or positive effects are reported.
516 Further studies at sites across the Arctic and sub-Arctic are necessary to understand the
517 effects of geese on sympatric species across a range of ecological conditions. Broad-scale
518 studies at multiple sites could help in identifying any population-level effects of geese on
519 these species as different wildlife communities may respond differently to goose
520 interactions. We also advocate for landscape- and local-scale studies since our review
521 suggests it is at these scales that geese appear to have the greatest impact on other
522 wildlife communities.

523 Analyses relating the densities of “cover-nesting” and “open-nesting” bird species
524 to potential habitat alteration using distance from goose colony as a proxy for impact
525 would be able to shed light on habitat-related effects of geese. In such a study, we predict
526 that if the effects of geese are a consequence of habitat alteration, then the densities of
527 cover-nesting and open-nesting species would show neutral/positive and negative
528 relationships, respectively, with distance from goose colony.

529 The effects of geese on invertebrate communities may vary by site based on
530 degree of habitat alteration or invertebrate community composition. Continued studies of
531 goose-invertebrate community interactions are needed, as are prey availability studies

(McKinnon et al. 2012; Bolduc et al. 2013) that incorporate goose-effect components. Studies on aquatic ecosystems that attempt to track the flow of goose-related nutrient inputs through the food web would be especially useful.

Studies of predator-prey interactions are common at many Arctic-monitoring sites; therefore, collaboration among research programs, with a focus on the effects of geese on other faunal communities should be encouraged. Again, these interactions may vary between study systems with different communities.

Research programs examining how light geese influence other species have already been initiated at Bylot, Southampton, and Coats Islands in the eastern Arctic, and the Queen Maud Gulf Migratory Bird Sanctuary in the Central Arctic. Studies are now also being initiated in Alaska, where growing goose populations are just beginning to create localized habitat change.

Conservation is increasingly focused on multispecies approaches where populations are managed in accordance with the population objectives of other species (NAWMP 2012, 2013). Sustainable population objectives for Arctic-nesting geese should therefore acknowledge the habitat needs of other species. However, adequate knowledge of these needs and how geese affect them is clearly lacking. The urgency is underscored by the significant population declines documented in at least nine Arctic shorebird species (Gratto-Trevor et al. 2011; Andres et al. 2012; North American Bird Conservation Initiative Canada 2012; North American Bird Conservation Initiative, U.S. Committee 2014) whose ranges overlap with those of breeding light geese. There are many potential factors underlying these declines, and the various effects of geese on sympatric wildlife, are only one of the potential contributing causes. However, for

shorebirds and other arctic wildlife, the impacts of hyperabundant geese have yet to be fully quantified. These impacts may be negligible or limited to specific geographic regions, or may be serious and broad-scale, affecting other species wherever their ranges overlap with those of geese. A better understanding of the potential effects of hyperabundant geese on other wildlife communities, from habitat alteration to predation, is critical to conserving Arctic ecosystems.

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Figure Captions

Fig. 1. Summer distributions of Snow (Lesser and Greater) and Ross' Geese across Arctic Canada with locations mentioned in text. Distributional data for geese were derived from airborne photo censuses (Kerbes et al. 2014), visual aerial surveys and other sources (J. Ingram personal communication, 2015; Ridgley et al. 2007). The map was created using Global Administrative Areas (GAA 2016) data.

Fig. 2. The proportion of available habitats, as classified in the Circumpolar Arctic Vegetation Map (CAVM 2003), falling within the currently published range maps for light geese.

Fig. 3. Potential indirect interactions between geese and sympatric species.

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