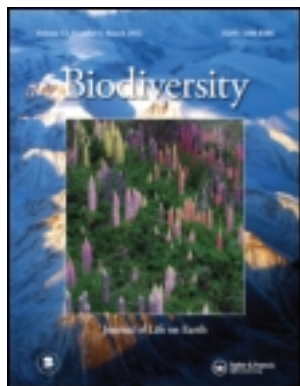




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Recent climate-related terrestrial biodiversity research in Canada's Arctic national parks: review, summary, and management implications

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Recent climate-related terrestrial biodiversity research in Canada's Arctic national parks: review, summary, and management implications

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It is now well documented that Arctic climates and ecosystems are changing at some of the fastest rates on planet Earth. These changes are significant for all Arctic biodiversity, and they are a great challenge for cooperative management boards of Canada's Arctic national parks, those legislated to maintain or improve the ecological integrity of all national parks. Owing to the inherent complexity of natural ecosystems, it is not at all clear how, nor how rapidly, these ongoing changes will affect park biodiversity and impact the traditional land-based lifestyles of Indigenous park cooperative management partners. In this context, this paper reviews and integrates recent research carried out in Canadian Arctic national parks: (1) *geophysical* – a reduction in glacial area and volume, active layer thickening, warming soil temperatures, and terrain instability; (2) *vegetation* – widespread but ecosystem-specific increases in NDVI 'greenness', plant biomass, shrub and herb coverage, and growing season lengths; and (3) *wildlife* – complex changes in small mammals and ungulate populations, very negative effects on some polar bear populations, and relatively stable mammalian predator and raptor populations at this time. This work provides a partial snapshot of ongoing and evolving ecological effects of climate change in Arctic national parks, and provides a strong foundation for prioritising future research and monitoring efforts. These evolving changes also undermine the historical paradigm of place-based conservation and necessitate a new approach for managing protected areas that involves acceptance of ongoing transformational change and adoption of a risk-based, forward looking paradigm in a changing world. It is proposed that Arctic national parks are ideal locations to focus Arctic science, especially as a component of a strategic, coordinated, and pan-Arctic approach to Arctic research that makes the most effective use of limited resources in the vast areas of Canada's north.

Keywords: Arctic protected area; Arctic biodiversity; climate change; climate adaptation; protected area management

Introduction

Canada's 12 northern national parks (Figure 1) cover a combined area of over 316,000 km², and have been strategically established through the Parks Canada Agency (PCA) Systems Plan (PCA 1997) to represent a cross-section of Arctic, sub-Arctic, and boreal climates, landscapes, and biota. Most Arctic parks have been established in the last 30 years, and five of the Arctic parks shown in Figure 1 have been established since 2001, as components of land claim settlements. As a result, traditional cultural activities in these parks are

maintained, and parks are managed through cooperative management boards that include local Indigenous communities.

Northern national parks are managed according to direction laid down in the Canada National Parks Act (CNPA 2000) to '... maintain or restore the ecological integrity of all national parks', and in accordance with goals in the various treaty agreements. National parks in the western Arctic in the Inuvialuit Settlement Region, for example (Ivvavik, Tukturnogait, and Aulavik NPs), are managed to meet the obligations of

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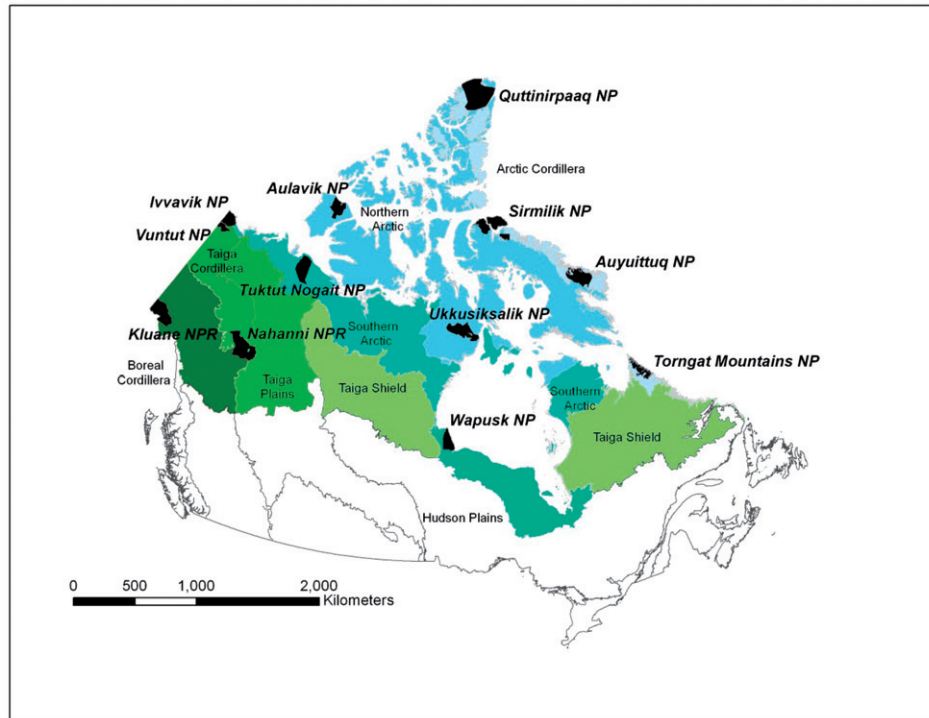


Figure 1. Location and ecological representation by ecoregion of northern national parks discussed in this paper. NP = National Park; NPR = National Park reserve.

the Inuvialuit Final Agreement (IFA 1987), which has as a goal ‘... the protection and preservation of Arctic wildlife, environment, and biological productivity through the application of conservation principles and practices’. Ecological integrity is defined in the Canada National Parks Act as ‘... a condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biological communities, rates of change and supporting processes’ (CNPA 2000).

As discussed in this paper, climate warming is driving ecosystem change across northern Canada (Post et al. 2009; Gilg et al. 2012) and these changes will fundamentally alter ecosystem processes and the species composition of northern national parks – changes that will challenge park managers charged with mitigating biodiversity loss and sustaining land-based lifestyles. One of the keys to successful adaptation to these inevitable changes is to attempt to understand how park ecosystems are changing through the strategic application of ecosystem monitoring and research in and around northern national parks (McLennan 2011). Knowledge derived from these activities will help park managers anticipate the most important changes and permit more proactive and creative adaptation strategies (Heller and Zavaleta 2009; Lawler 2009; Lindenmayer and Likens 2009).

It is within this management context that this synopsis is undertaken. Although the focus of this report is Arctic landscapes, examples from sub-Arctic and boreal parks are presented as well.

Cryosphere changes – northern national parks are thawing

The amplification of global temperature increases at northern latitudes that has been widely reported (ACIA 2005; Anisimov et al. 2007; Barber et al. 2008; Derksen et al. 2012) is reflected in weather records from stations in and around national parks. At Old Crow (Figure 2), adjacent to Vuntut NP, mean daily temperatures for all months have been between 7 and 12°C warmer since 1997, compared to the monthly mean daily averages for the 1951–1980 period, especially in the fall and winter. At Pond Inlet (adjacent to Sirmilik NP), a similar but less dramatic pattern has occurred over the last 35 years, where mean spring and summer temperatures show an average increase of 2.8°C, while fall mean temperatures have increased 4.3°C (Gauthier et al. 2011). These increases reveal greater change in the western compared to the eastern Arctic, and are more than twice as large as for southern North America over the same period (IPCC 2007).

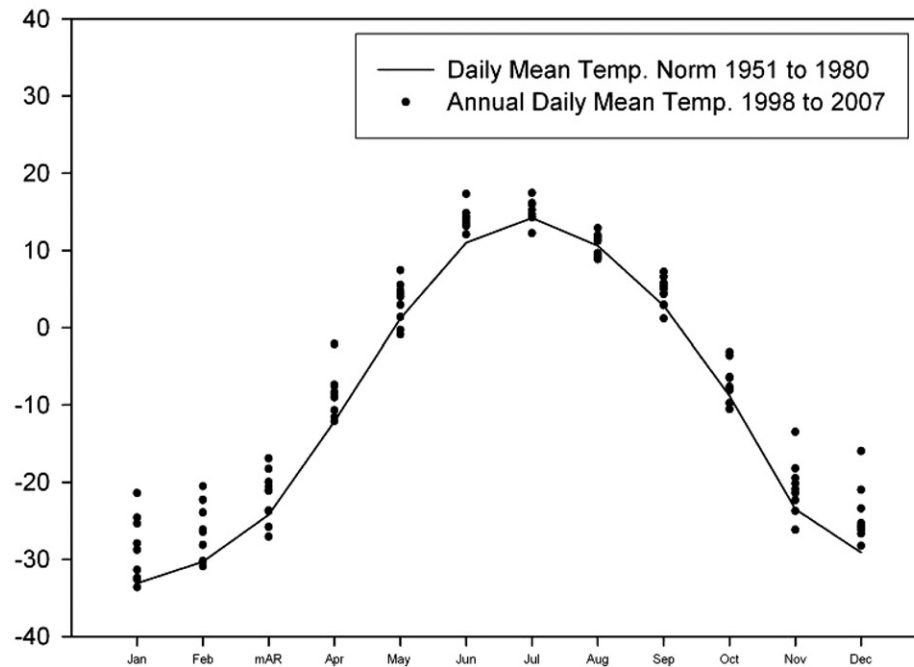


Figure 2. Comparison of mean daily temperatures at Old Crow, Yukon, during 1951–1980 (line) with the more recent 1998–2007 period (dots).

Source: EI monitoring program, Yukon Field Unit (PCA 2007).

The terminus of the Kaskawulsh Glacier in Kluane NP retreated by an average of 655 m between 1956 and 2007, most of which occurred since 2003 (Foy et al. 2011), and is consistent with other glaciers in the area (Barrand and Sharp 2010; Berthier et al. 2010). Glaciers in Torngat Mountains NP lost almost one-tenth of their area between 2005 and 2008; over 80% of Torngat glaciers are now smaller than 0.25 km² and typically occupy shaded areas beneath high backwalls of cirque basins (Brown et al. 2012). Major decreases in glaciers and ice caps through calving and negative surface mass balance have been reported since 2000 in the Canadian Arctic Archipelago (Dowdeswell et al. 2007; Gardner et al. 2011; Sharp et al. 2011; Mueller, Copeland, et al. 2008), which includes ice fields in Auyuittuq, Sirmilik, and Quttinirpaaq NPs. These losses are tied directly to anomalous summer warming since 2005 (Gardner et al. 2011), resulting in higher surface temperatures and longer melt seasons (Sharp et al. 2011). This warming has driven a similar loss in multi-year landfast ice in and around Ward Hunt Island in Quttinirpaaq NP (Vincent, Fortier, et al. 2011), accelerating a process of ice loss that has been ongoing for the last 50 years.

Reductions in glacial area are important for a number of reasons. In addition to the indirect impact of ice loss on terrestrial, freshwater and adjacent marine ecosystems, ice ecosystems harbour unique assemblages of cold-hardy microbial communities

that are now threatened (Vincent, Mueller, and Bonilla 2004; Vincent 2010). Furthermore, glacial melting in the Canadian Arctic Archipelago is the largest source of sea level rise outside of Greenland and Antarctica, with mass losses over the period 2004–2009 contributing 0.17 mm to global sea level rise (Gardner et al. 2011). Glaciers are also iconic landscape features important to Indigenous cultures, and to park visitors.

Temperature records collected over the past two to three decades indicate that permafrost is warming across northern Canada (Smith et al. 2010). While there is some evidence that summer thaw depths have increased at some sites, long-term trends are less evident because active layers respond to shorter-term variations in temperature, and the records show a great deal of inter-annual variability (Burn and Kokelj 2009; Smith et al. 2010). Tarnocai, Gould, and Achuff (2009) recorded increases in soil temperature and resultant increases in summer active layer depth between 1990 and 2008 in Quttinirpaaq NP (Figure 3). Changes in summer thaw depth are an important causative factor that can initiate retrogressive flow slides, degraded ice wedges and detachment slides (Tarnocai et al. 2001; Broll, Tarnocai, and Gould 2003), events that can introduce fine sediments into streams and impact water quality and aquatic habitats. Related processes in polygonal, ice-rich ground in Sirmilik NP are draining wetlands and creating more mesic tundra ecosystems

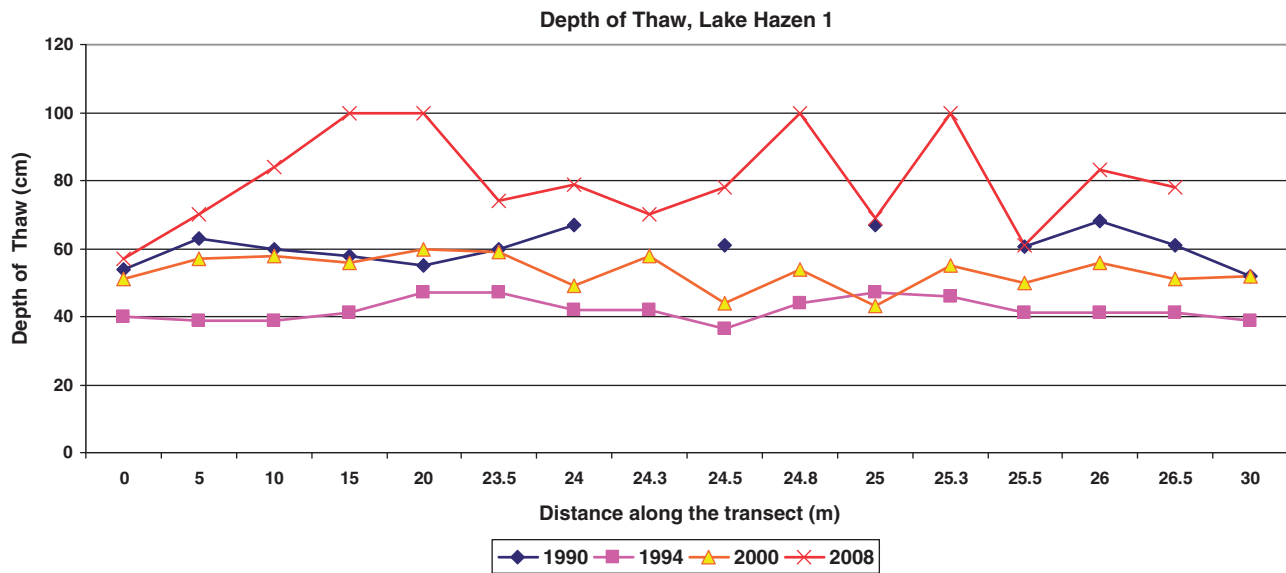


Figure 3. Increases in depth of thaw between 1990 and 2008 in the Lake Hazen area, Quttinirpaaq NP. Source: Tarnocai, Gould, and Achuff (2009).

(Fortier, Alard, and Shur 2007; Godin and Fortier 2010, 2012). Mass wasting events and permafrost warming also threaten park infrastructure and may create safety issues for park visitors.

Dyke and Sladen (2010) predicted that, in the extensive wetlands of Wapusk NP, permafrost under peat plateaus would be relatively stable, and that permafrost under fens and the edges of peat plateaus would be more susceptible to climate warming. Work by Gamon et al. (2012) in the same region supports this assessment, postulating that thermal feedbacks between troughs and plateau surfaces contribute to a long-term stability of peat plateau landforms. Active layer and permafrost modelling over Wapusk NP by Zhang et al. (2012) predicted that the active layer deepened by an average of 37% across the park, and that permafrost degraded completely in some areas of the southern part of the park over the twentieth century.

Warming Arctic soils overlying permafrost contain large quantities of very old organic carbon that, if released, have the potential to impact atmospheric carbon balance and global temperatures (Ping et al. 2008; Schurr et al. 2008). Tarnocai et al. (2009) estimated that soils in the northern permafrost region contain 1672 Pg of organic carbon, an amount that is more than double the amount in the atmosphere, and more than 10 times the organic carbon in all above-ground biomass. The fate of this old organic soil carbon at northern latitudes will be a balance between what is decomposed and lost to the atmosphere, and what is taken up by warming permafrost-affected soils

and increasing Arctic vegetation biomass (ACIA 2005; Tarnocai et al. 2009; Hartley et al. 2012). Schurr et al. (2008) concluded that carbon contributions from thawing permafrost would result in a net contribution of organic carbon from Arctic soils. Recent work by Hartley et al. (2012) suggests that invasion of tundra by trees may actually stimulate soil carbon emissions, due to the priming effects of tree roots on ancient soil carbon. Arctic national parks will vary tremendously in their potential contributions to atmospheric carbon. For example, Wapusk NP on the Hudson Bay Coastal Plain is a 10,000 ha area underlain by a continuous layer of organic peat, whereas many northern or mountainous parks such as Torngat Mountains or Quttinirpaaq have few wetlands, so carbon contributions will be principally from old carbon stored in mineral soils. Given their large area, this research suggests that ancient carbon presently contained in permafrost and near surface soils of northern national parks has the potential to make a globally significant contribution to the atmospheric carbon pool as climates warm.

Despite its critical role in the functioning of the physical (Vincent, Callaghan, et al. 2011), vegetation (Callaghan et al. 2011), and animal (Mech 2004; Reid et al. 2012) components of northern terrestrial ecosystems, long-term monitoring and research on snow is rare, inside or outside national parks (Vincent, Callaghan, et al. 2011). Kershaw and McCulloch (2007) showed that inter-annual variation in snow depth, density, and snow water equivalent was much higher than local scale site variability, along a

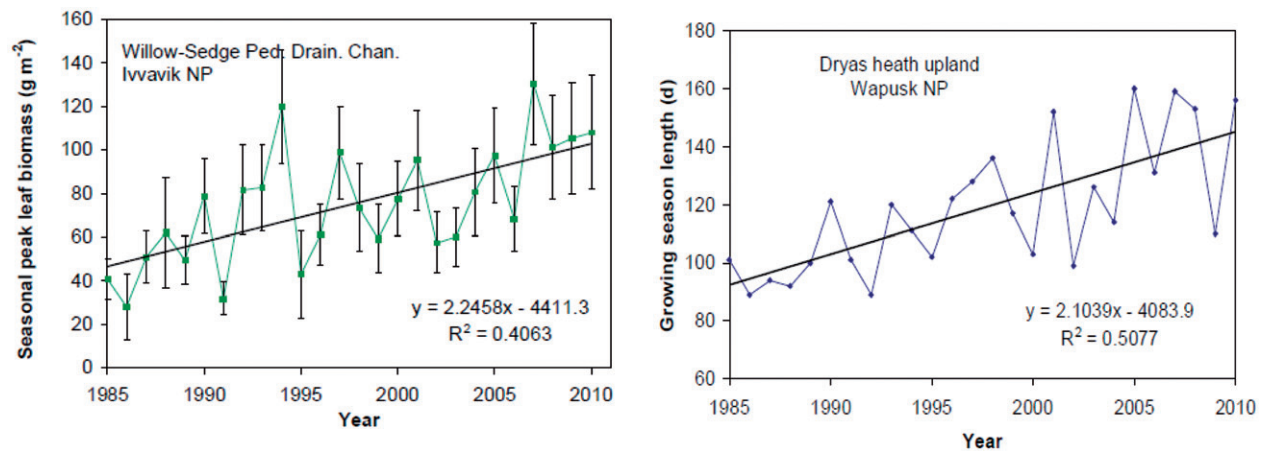


Figure 4. Seasonal peak leaf biomass (g m^{-2}) more than doubled between 1985 and 2010 in the willow sedge pediment drainage channel ecotype in Ivvavik NP. The growing season increased on average by over 40 days in the same period. Source: Chen et al. (2012).

transect that crossed sub-Arctic forest into coastal tundra in Wapusk NP. Satellite-based programs reveal that, at the scale of the Arctic, overall onset of fall snow has remained relatively unchanged, whereas June snow cover extent has decreased by 46% between 1967 and 2008 (Brown, Derksen, and Wang 2010; Derksen and Brown 2011). Although considerable progress was made in remote sensing of snow parameters during the IPY period (Derksen et al. 2012), systematic snow monitoring at scales relevant to local scale applications such as protected areas management is lacking (Brown, Walker, and Goodison 2000).

Vegetation change – the ‘greening’ of northern national parks

Significant declines in the area of summer sea ice between 1982 and 2008 in the circumpolar Arctic (Stroeve et al. 2011) have been linked to warmer land temperatures, with an estimated 30% increase in summer warmth index in the North American Arctic over this period (Bhatt et al. 2010). This land warming has also been linked to a widely reported ‘greening of the Arctic’, as expressed through increases in satellite-derived normalised difference vegetation index (NDVI) across broad Arctic and sub-Arctic terrestrial areas (Jia and Epstein 2003; Lawrence et al. 2008; Jia, Epstein, and Walker 2009; Bhatt et al. 2010). Fraser et al. (2011) conducted analyses of NDVI and land cover changes in Torngat Mountains, Wapusk, Sirmilik, and Ivvavik NPs, demonstrating a 6 to 25% increase in NDVI across all parks over the last 23 years, with associated increases in shrub and herbaceous cover. Using a sub-pixel fractionation approach on archived Landsat

data, Fraser et al. (2012) showed that, between 1985 and 2006, low shrubs increased between 50 and 100%, replacing herbaceous cover and bare ground at elevations below 300 m, while herbs increased between 25 and 50%, replacing bare ground at elevations above 300 m in Torngat Mountains NP (see Figure A1 in the Appendix). Increases in greenness, and in shrub and herb cover, can account for linear increases in seasonal peak leaf biomass between 1985 and 2010 for Torngat Mountains, Sirmilik, Wapusk, and Ivvavik NPs (Figure 4), as shown by Chen et al. (2012). All four parks studied by Chen et al. (2012) also showed important increases in the length of the growing season using temporal seasonal analysis of NDVI.

Long-term monitoring of tundra vegetation at sites around the Arctic and in alpine areas has revealed increases in height and cover of shrub species, and decreases in the cover of bare ground (Elmendorf et al. 2012). This biome-level synthesis indicated an association between local summer warming and local changes in plant abundance, which was dependent on the climate zone, moisture regime, and presence of permafrost. In Sirmilik NP, Gauthier et al. (2011) reported an 85% increase in plant biomass between 1990 and 2010 in a sedge wetland. Changes in the relative species dominance of Arctic grasses (Kennedy, Smith, and Cooley 2001) and a willow species (Myers-Smith, Hik, et al. 2011) were observed over three decades in Ivvavik NP on the Yukon Slope, and on adjacent Herschel Island. Myers-Smith, Hik, et al. (2011) used photographs and growth ring analysis to show localised increases in shrubs on Herschel Island, building on strong photographic and satellite-based evidence for shrub expansion in neighbouring Canada and Alaska (Sturm, Racine, and Tape 2001;

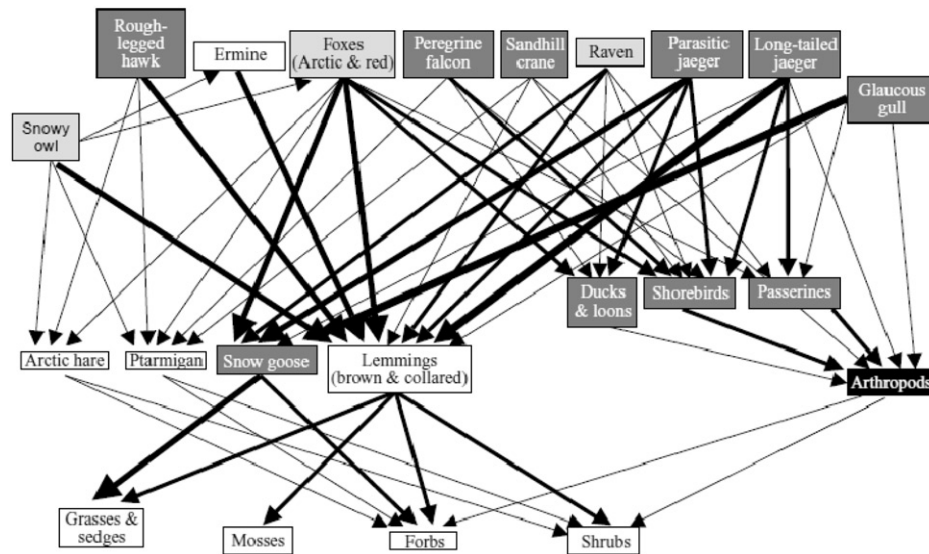


Figure 5. Bylot Island (Sirmilik NP) food web showing four species categories: migrant (dark grey), partial migrant (light grey), resident, (white), and resident frozen in the soil during winter (black). Line thickness indicates the relative strength of interactions between species.

Source: Gauthier et al. (2011).

Tape, Sturm, and Racine 2006; Myers-Smith, Forbes, et al. 2011). Myers-Smith (2011) used growth rings and age distribution to document an upslope movement of tall willow communities in alpine tundra in Kluane NP.

Hudson and Henry (2010) reviewed International Tundra Experiment (ITEX) results between 1992 and 2008 at Alexandra Fiord adjacent to Quttinirpaaq NP and found an increase in the abundance of evergreen shrubs and bryophytes, but no change in deciduous shrub, forb, graminoid, and lichen cover. Hudson and Henry (2009, 2010) and Elmendorf et al. (2012) reported regional and local variability in the response of Arctic vegetation to experimental warming, and that factors other than temperatures were also important in vegetation response. The overall ITEX observation that plant response to climate warming may be partially site dependent (Hudson and Henry 2009; Hudson, Henry, and Cornwell 2010; Elmendorf et al. 2012) is supported by satellite-based analyses that indicates faster rates of biomass increase on moister sites, as estimated from topographic wetness modelling and qualitative estimates of soil moisture regime from ecosystem mapping (Nalto and Cairns 2011; Chen et al. 2012). These results suggest that warming is increasing plant growth in northern national park ecosystems in complex ways, where response will depend on species and sites. Feedbacks between new community structures and environmental factors such as winter snow accumulations will further complicate predictions of ongoing change (Shaver et al. 2006; Hill and Henry 2011).

Arctic food webs

Arctic terrestrial ecosystems are characterised by two major food web types – those where large herbivores such as barren ground caribou range across a wide territory consuming large vegetation biomass and supporting large predator populations such as grey wolf, golden eagle, and wolverine, and those where large herbivore herds and their key predators are absent (Krebs et al. 2003; Gauthier et al. 2011). Gauthier et al. (2011) developed a food web model based on biomass flux among trophic levels (Figure 5) and determined that, in terrestrial ecosystems like Sirmilik NP where large herbivores are absent, top down pressure from local and wide-ranging predators was the principle control on cyclic lemming populations. This analysis revealed that less than 10% of the annual plant production at the landscape level is consumed by herbivores (primarily lemmings and geese), and that 20 to 100% of the annual herbivore production is consumed by predators (Legagneux et al., 2012). Presumably, these two food web systems are not spatially exclusive, so that, in parks like Ivvavik, Vuntut, and Tuktut Nogait, herds of migratory caribou consume a large biomass of vegetation and support their predators seasonally, at the same time as mobile raptors and smaller predators such as red and Arctic fox, and ermine interact with cyclic lemming populations over the course of the year. Highly abundant snow geese are locally important as a prey source where they stage and nest in parks like

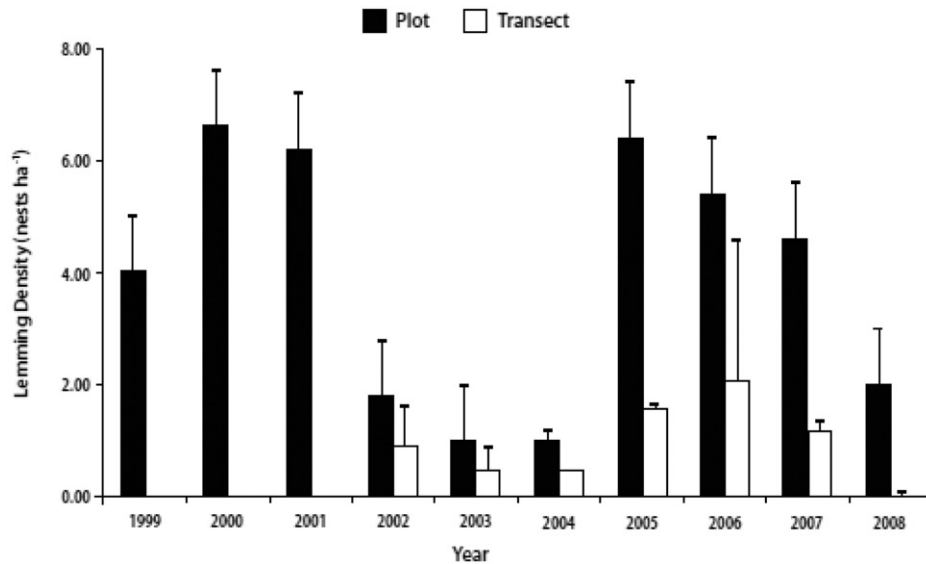


Figure 6. Lemming nest density in Aulavik NP from 1999 to 2008. Error bars represent 95% confidence limits around annual abundance estimates.

Source: EI monitoring program, Western Arctic Field Unit (PCA 2009).

Sirmilik and Wapusk. In Wapusk NP in particular, snow geese staging and nesting populations are sufficient to have progressively degraded large areas of the estuarine and wetland ecosystems where they forage (Jefferies, Rockwell, and Abraham 2003; Jefferies, Jano, and Abraham 2006; Rockwell et al. 2009).

The work by Gauthier et al. (2011) and work reviewed in Gauthier and Berteaux (2011) point to the broad geographic range of many species that are present in Sirmilik NP (Figure 5). Mobile park predators such as snowy owls, range across broad areas of the Arctic; long-range migrants such as shorebirds rely on seasonally-available insect emergence for optimum nutrition of nestlings (Moltofte et al. 2007; McKinnon et al., 2012); snow geese provide a large input of nutrients subsidised by agricultural ecosystems in the southern United States (Giroux et al., 2012) and Arctic foxes range widely on sea ice in the winter (Tarroux, Berteaux, and Bêty 2010). These observations emphasise the reliance of park ecological integrity on ecosystems and factors well beyond park boundaries.

The keystone role of lemmings

The work on food webs in Sirmilik (Figure 5) clearly demonstrates that lemmings and voles play a very important keystone role supporting Arctic biodiversity because of their widespread but cyclic abundance, and their consequent role as prey for many Arctic raptors and mammalian predators (Gauthier et al. 2004, 2011;

Gauthier and Berteaux 2011; Therrien 2012). In Sirmilik NP, brown and collared lemmings show cyclic, 3–4 year oscillations that fluctuate synchronously, with collared lemmings having lower amplitude cycles compared to brown lemmings (Gruyer, Gauthier, and Berteaux 2008, 2010). Although not fully understood, typical cycling of lemming populations (Figure 6) is thought to be mostly the result of large population increases under favourable winter snow conditions, followed by increased densities of predators that eventually result in declines in lemming numbers (Gilg, Hanski, and Sittler 2003; Gauthier et al. 2011; Krebs et al. 2011; Legagneux et al., 2012). Local predators such as Arctic fox, weasels, and long-tailed jaegers respond to lemming peak years by higher reproduction rates, while wide-ranging species such as snowy owl migrate across broad distances to take advantage of abundant prey (Therrien 2012).

The interaction of blowing snow with micro- and mesoscale ground topography and vegetation cover causes variable snow depths during the winter, and concentrates lemming nesting in areas where snow is sufficiently deep to create conducive sub-nivean thermal conditions (Duchesne, Gauthier, and Berteaux 2011). Recent snow fence experiments in Sirmilik and Ivvavik NPs, and on Herschel Island (Reid et al. 2012), identified a threshold of 60 cm snow depth to create desirable thermal conditions for enhanced sub-nivean reproduction of brown lemmings and tundra voles. Warm winters, low snow accumulation and winter rain events have been cited as the principle factors behind low lemming productivity and high mortality in Greenland and parts of Europe

(Kausrud et al. 2008; Gilg, Sittler, and Hanski 2009), a trend sufficient to suggest the collapse of these cycles (Ims, Henden, and Killengreen 2008). To date there is no conclusive evidence to suggest a similar situation in the Canadian Arctic (Gauthier et al. 2011; Krebs et al. 2011).

Arctic raptors – following the lemmings

The local abundance and reproductive success of many avian predators, including snowy owls, short-eared owls, rough-legged hawks and long-tailed jaegers, are strongly related to lemming abundance (Therrien 2012). Reid et al. (forthcoming) suggested that a minimum density of 4 lemmings/ha is required to support short-eared owl nesting, based on work in Ivvavik NP and the Yukon north slope. Snowy owls breed in Sirmilik NP typically every 3–4 years, and only at high lemming densities (Gauthier et al. 2004). Satellite-tracking of snowy owls confirms that these birds move long distances between breeding seasons (Therrien 2012). These movements allow snowy owls to find areas where lemmings are abundant, and thus to breed almost every year over a wide range of territory (Therrien, Gauthier and Bêty 2012). The most surprising result was that the snowy owls spend up to 101 days on the sea ice between December and April to prey on seabirds using open water leads (Therrien, Gauthier, and Bêty 2011).

Arctic fox and red fox

Fluctuations in lemming abundance generate oscillations in Arctic fox reproductive output and, consequently in the predation pressure imposed by Arctic fox on secondary prey species such as geese and shorebirds (Gauthier et al. 2004). Arctic Foxes breeding in Sirmilik NP use an area that extends up to 500 km from the park in winter and spring, where they travel on sea ice in search of offshore prey (Tarroux, Berteaux, and Bêty 2010). Traditional ecological knowledge indicates that red foxes have invaded the eastern Arctic only in the last decades (Gagnon and Berteaux 2009). Where their ranges overlap, the two fox species may compete for resources and the red fox is often dominant (Pamperin, Follmann, and Petersen 2006). In Ivvavik, however, Gallant et al. (2012) concluded that red fox is not yet replacing Arctic fox, based on comparing present den occupation with occupation surveyed in the 1970s and the 1980s. As climate ameliorates across the Arctic, the ongoing relationship between red and Arctic fox is an early example of many more complex inter-specific interactions that will inevitably occur as southern species

move into the ranges of established species in more northern national parks.

Barren ground caribou – Arctic Serengeti

All mainland northern national parks provide habitat for the large herds of barren ground caribou that dominate many southern Arctic landscapes. The caribou herds support a wealth of predator biodiversity and are an important source of food sustaining the health and culture of northern communities. Most importantly for national parks, Ivvavik NP includes a major portion of the calving area of the Porcupine Caribou Herd, and Tuktut Nogait NP includes almost all of the calving area of the Bluenose West Caribou Herd. Population trends in the Porcupine (Ivvavik NP, Vuntut NP), Bluenose West (Tuktut Nogait NP), and George River (Torngat Mountains NP) herds (Figure 7) are typical of the circumpolar pattern where most herds peaked in the early 1990s, and have been decreasing since that time (CARMA 2012). Population fluctuations are interpreted to be a natural cycle caused by the interaction of long-term climate cycling with forage quality and calf survival (Griffith et al. 2002; Gunn 2003; Payette et al. 2004; White 2008; Sharma, Couturier, and Côté 2009). Some herds are showing signs of recovery, e.g. Porcupine, Leaf, and Bluenose East, while others are stable or continuing to decline (CARMA 2012). The depth of the period of low abundance, and the ability to recover from such low numbers, may now be affected by anthropogenic stressors including mineral exploration and development, hydroelectric developments, and overhunting resulting from the improved access to herds provided by snow machines, and increasing pressure to develop

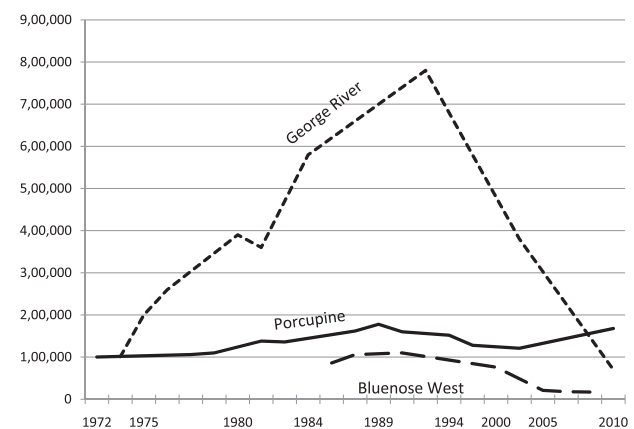


Figure 7. Population trends in three barren ground caribou herds occurring in Arctic national parks: Porcupine Herd in Ivvavik NP, Bluenose West Herd in Tuktut Nogait NP, and George River Herd in Torngat Mountains NP. Source: CARMA (2012).

all-weather roads (Griffith et al. 2002; Gunn 2003; White 2008; Sharma, Couturier, and Côté 2009; CARMA 2012; Joly, Duffy, and Rupp 2012). Climate change may also impact herd recovery through earlier onset of the growing season, where caribou arrive in the calving grounds after the vegetation has passed through its optimal stage of nutrition (White 2008; Sharma, Couturier, and Côté 2009), with important potential effects on calf survival and population recovery. Potential increases in burned area through predicted climate-driven increases in forest fires that destroy the lichens critical to foraging in caribou wintering areas has also been put forward as an important factor complicating cyclic population recovery (Joly, Duffy, and Rupp 2012). These negative factors need to be balanced against the potentially positive effects of increased biomass of caribou forage, and overall warmer temperatures (Jefferies et al. 1992; Griffith et al. 2002).

Peary caribou – a species in crisis

Peary caribou in national parks on the Arctic islands are presently at very low numbers, and in 1994 were listed as ‘endangered’ (COSEWIC 2004) following catastrophic die offs (Miller and Gunn 2003). Die offs have been associated with mild fall weather where freeze thaw cycles and deep snows deny access to food, create injuries and provide better mobility for predators (Miller, Barry, and Calvert 2007; Miller and Barry 2009). Peary caribou on Bathurst Island (soon to be a national park) declined 98% between 1995 and 1997 as a result of heavy snow and icing (Miller and Gunn 2003). Although Peary caribou have been through these genetic funnels in the past (COSEWIC 2004), the species has recently been assessed by Festa-Bianchet et al. (2011) as being at a considerable risk of extinction. Tews, Ferguson, and Fahrig (2007) predicted that Peary caribou population recovery will depend on the balance between the nutritional benefits of enhanced vegetation productivity, and the deleterious effects of icing and other negative factors. Such debates are typical of the uncertainty surrounding the future of Arctic biodiversity.

Polar bears – icons of the north

The most southerly Arctic national parks (Wapusk NP, Torngat Mountains NP, Ivvavik NP) provide important off-ice refuge and denning areas for polar bears, and recent studies are showing that some of these southern populations are in decline or threatened because of decreasing summer sea ice (Stirling and Parkinson 2006; Rode, Amstrup, and Regehr 2010;

Stirling et al. 2011; Stirling and Derocher 2012). Wapusk NP was established to protect maternal denning areas of the Western Hudson Bay population, and ongoing monitoring has shown that mean body mass of adult female bears declined by 22% between 1980 and 2004.

Ongoing studies are now documenting the linkages between declining sea ice and population and recruitment declines in Beaufort Sea and Western Hudson Bay polar bear populations (Derocher, Lunn, and Stirling 2004; Stirling and Parkinson 2006; Regehr et al. 2007, 2010; Wiig, Aars, and Born 2008). Molnar et al. (2011) used mechanistic energy models of the Western Hudson Bay population to demonstrate a 28% increase in female bears that failed to reproduce in the 1990s, and projected increases of 40–73% with a one month increase in the ice free season, and a 44–100% increase in a two month increase. A similar pattern is being documented for the Southern Beaufort Sea population that uses Ivvavik NP, where decreasing multi-year summer sea ice will cause bears to move north, and is already causing tell-tale signs of population stress, including increased rates of drowning, cannibalism, infanticide, reduced food intake and survival, and lower body growth rates (Derocher 2012; Stirling and Derocher 2012). Given the projected decline in Arctic sea ice and the obligate relationship that polar bears have with ice-based seal prey, a number of recent modelling studies predict a significant to drastic decline in southern Arctic polar bear populations over the twenty first century (Wiig, Aars, and Born 2008; Durner et al. 2009; Hunter et al. 2010), and these projections have led to an ‘endangered’ ranking under the US Endangered Species Act. In a recent review, Stirling and Derocher (2012) predict that, at present rates of climate warming and sea ice loss, southern populations of polar bears such as those in Wapusk and Ivvavik NPs will likely disappear within 30–40 years.

Summary and discussion

Ongoing warming across northern Canada is resulting in significant changes to park cryospheres and vegetation in northern national parks. Glaciers are retreating, permafrost and soils are warming, summer thaw depths appear to be increasing, and summer sea ice extent is decreasing. To date there is little evidence of in-migration of new plant species at arctic sites. Currently observed vegetation changes include increases in plant productivity resulting in significant changes in tundra community structure – changes that have the potential to create a complex, multi-scalar ecological cascade where impacts will range from local

scale effects on habitats and soil processes (Sturm, Schimel, et al. 2005; Post et al. 2009), to watershed effects on hydrology (McFadden et al. 2001), to global effects on climate through vegetation–atmosphere feedbacks (Sturm, Douglas, et al. 2005; Bonfils et al. 2012), and to ‘leakage’ of permafrost and soil carbon (Ping et al. 2008; Schurr et al. 2008; Tarnocai et al. 2009).

Compared to observed changes in cryosphere and vegetation, faunal responses to climate warming at this time are, for the most part, less clearly linked to observed changes in climate. For example, barren ground caribou have been decreasing across the circumpolar Arctic following very high population peaks for most herds in the early 1990s. These changes are mostly attributed to historical long-term cycling, and some herds are now showing signs of recovery (CARMA 2012). Others attribute the recent declines more directly to climate-driven processes and question the ability of herds to recover, given anthropogenic stressors (Vors and Boyce 2009). This creates considerable uncertainty around the future of the large barren ground caribou herds that are iconic features of northern national parks and Arctic landscapes, key drivers of Arctic biodiversity and ecosystem processes, and central to community culture and land-based lifestyles. A similar uncertainty exists around Peary caribou – a species that has recently been devastated by factors related to a changing climate (Miller and Gunn 2003), but who may potentially recover if increases in forage productivity outweigh the negative effects of climate warming (Tews, Ferguson, and Fahrig 2007).

Whereas in northern Europe and Greenland there is convincing evidence that climate change is impacting lemming numbers and the predators that rely on them (Kausrud et al. 2008; Gilg, Sittler, and Hanski 2009), there is little evidence for this so far in Canada (Gauthier et al. 2011; Krebs et al. 2011). Given their keystone role in Arctic food webs, the future of lemming population dynamics will directly and indirectly make a significant impact on the faunal biodiversity of all Arctic national parks. Difficulties inherent in predicting changes in snow depth and phenology through climate modelling, and the natural local-scale variability in snowfall, create a key uncertainty in predicting the future of Arctic small mammals and the biodiversity they support.

One important exception to this unclear linkage between climate change and faunal effects is for some southern populations of polar bears, in particular the Western Hudson Bay (Wapusk NP) and Southern Beaufort Sea (Ivvavik NP) populations, where the disappearance of these populations over the next 30–40 years has recently been predicted (Stirling and Derocher 2012). It can be expected that reduced sea

ice will force populations north as predicted summer sea ice reductions occur, and the area around Quttinirpaaq NP has been designated a ‘last ice area’ for the species (WWF 2012). Recent genetic work (Hailer et al. 2012) traces the origins of polar bears back between 338,000 and 734,000 years, so much older than thought previously, suggesting that polar bears have been through these resource funnels in the past. As for the uncertainty around the future of barren ground caribou and Peary caribou, the rate of present climate change, and the added direct and indirect effects of anthropogenic stressors such as hunting and toxic loading, create serious difficulties in predicting the long-term fate of this iconic species.

Overall, although significant changes in Arctic fauna are inevitable, it appears that, at this time, these changes are only just beginning to occur. In the next few decades it can be expected that more mobile sub-Arctic and boreal species of songbirds, raptors, small mammals, ungulates, and predators will move north into southern Arctic national parks, creating complex interactions with Arctic species already present (ACIA 2005; Berteaux et al. 2006; Lawler 2009; Vincent, Callaghan, et al. 2011; Gilg et al. 2012). The immigration of southern species and a warming climate will put pressure on obligate Arctic species such as polar bears, muskox, lemmings, Arctic fox, and Peary caribou, that will either need to migrate or adapt (Berteaux et al. 2006; Berteaux and Stenseth 2006; Vincent, Callaghan, et al. 2011; Gilg et al. 2012). Understanding the potential role of refugia in harbouring species with contracting climatic envelopes will be important for predicting the fate of many obligate Arctic species (Stewart et al. 2010; Allen et al. 2012; Keppel et al. 2012). Areas of the Arctic with mountainous terrain, such as Ivvavik, Torngat Mountains, Auyuittuq, Sirmilik, and Quttinirpaaq NPs, have the potential to provide physiographic climate refugia either at elevation, or on north facing slopes. Christie and Sommerkorn (2012) have recently proposed a conservation process to identify such refugial areas across the circumpolar Arctic and propose them for protection.

There exists at this time a high level of uncertainty regarding how terrestrial ecosystems in northern national parks will respond to climate change. The first part of this uncertainty comes from the difficulties in predicting how climates will change at spatial and temporal scales relevant to protected areas managers (ACIA 2005; IPCC 2007; McLennan 2011), and the second from the inherent complexity of natural ecosystems (Krebs and Berteaux 2006). Given our apparent inability as a global society to act on the drivers of climate change, and the enormous scale and scope of the changes, managers of northern national

parks are presented with a situation where radical ecological change is inevitable. The key challenge for managers of northern national parks is to develop management strategies that will mitigate biodiversity loss and help navigate these inevitable changes in park ecosystems.

Managing northern national parks in a changing world

Canada's northern national parks deliver important ecological services to northerners and all Canadians, including providing places for the conservation of regional biodiversity, for the maintenance of traditional land-based lifestyles, and as areas of unparalleled beauty where park visitors can engage in and appreciate wild nature. As reviewed in this paper, ongoing climate-driven ecological change is expected to accelerate in the future, making it impossible for managers of national parks to '...maintain or restore the ecological integrity' (CNPA 2000) of northern national parks. These changes will also mean that the country food species that support the land-based lifestyles that Indigenous northerners have relied on for centuries to nourish their families and provide a spiritual connection to the land will also be fundamentally altered. These realities, in the regional context of increasing industrial development and associated activities, will challenge park managers to continue to provide expected ecological services for northern national parks.

Given the inevitability and geographic scale of ongoing and accelerating climate-driven ecological change, national park cooperative management boards and committees will need to shift their management context and goals from place-based, stationery concepts focussed on maintaining a desired condition of species and processes at ecological equilibrium, to a proactive, forward-looking, risk-based approach that acknowledges and plans for ongoing transformation of park ecosystems, and the ecological services they provide (Peterson, Cumming, and Carpenter 2003; Walker et al. 2004; Chapin, Folke, and Kofinas 2009; Chapin et al. 2009, 2010).

In this context, and given inherent uncertainties, a program of systematic and cost-effective monitoring that identifies and tracks a tractable suite of key abiotic and biotic elements of park ecosystems is a first priority for understanding how key attributes of Arctic national parks are changing (Lawler 2009; McLennan 2011). As discussed by Lindenmayer and Likens (2009), the monitoring itself needs to be adaptive so as to track new, important trends as they emerge. Park monitoring needs to be linked to a strategic park

research programme focussed on understanding and communicating changes in park ecosystems as they evolve. This understanding of changing ecosystem processes can then be linked to forward-looking, short and medium term, park-scale scenarios that create a range of possible futures in the context of key park issues (Peterson, Cumming, and Carpenter 2003; NPS 2012), as identified by park cooperative management boards, e.g. changes in park focal species such as caribou, Arctic char, lemmings, and species at risk; potential risks to visitor activities such as river rafting safety under changing hydrologic regimes, and back-country hiking; and potential risks to park infrastructure and cultural sites. This approach acknowledges inherent uncertainties in the predictions, and model results are used to develop potential management actions that will be effective in a range of potential futures (Peterson, Cumming, and Carpenter 2003).

Park species utilise broad areas far beyond the boundaries of national parks, so to be successful at reducing the potential impacts of change in park species and processes the cooperative-management boards of Arctic national parks will need to work with local, regional, national and international partners to promote the adoption of a pan-Arctic biodiversity conservation strategy – a strategy that must engage all northern stakeholders in a broad-scale plan to conserve Arctic biodiversity and traditional lifestyles, while permitting the careful development of Arctic resources that can help enrich northern communities. Under such a plan, national parks and other protected areas would become the anchors of a Canadian pan-Arctic conservation strategy.

Given the broad ecological representation of Arctic national parks (Figure 1), the field-based science summarised in this paper provides a synoptic overview of ecological change across the entire Canadian Arctic. In the context of broader, pan-Canadian and pan-Arctic research activities, this information can inform conservation policy and knowledge-based land use planning locally, nationally, and internationally, as will future research and monitoring activities carried out in national parks. The broad geographic coverage of Arctic national parks, along with park linkages to northern communities through land claim settlements, support for researchers by experienced park staff, and ongoing baseline inventories and monitoring, make national parks a highly strategic location for university and government scientists to focus limited research funds in the future. Along with existing research field facilities, a key step forward in optimising investments in Arctic research and monitoring is to develop coordinated studies that utilise this inclusive geographic representation to answer key questions at a

pan-Arctic scale, e.g. potential changes in the abundance and quality of country food, broad scale vegetation change, population studies of focal species, vegetation–atmospheric feedbacks, changes to the cryosphere, and carbon balance studies. Research conducted in national parks would thus serve a national and pan-Arctic agenda, while also providing critical information that would help park cooperative management boards navigate the inevitable and significant changes that lie ahead.

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Appendix

Predicted fractional land cover changes for Torngat Mountains NP are shown in Figure A1.

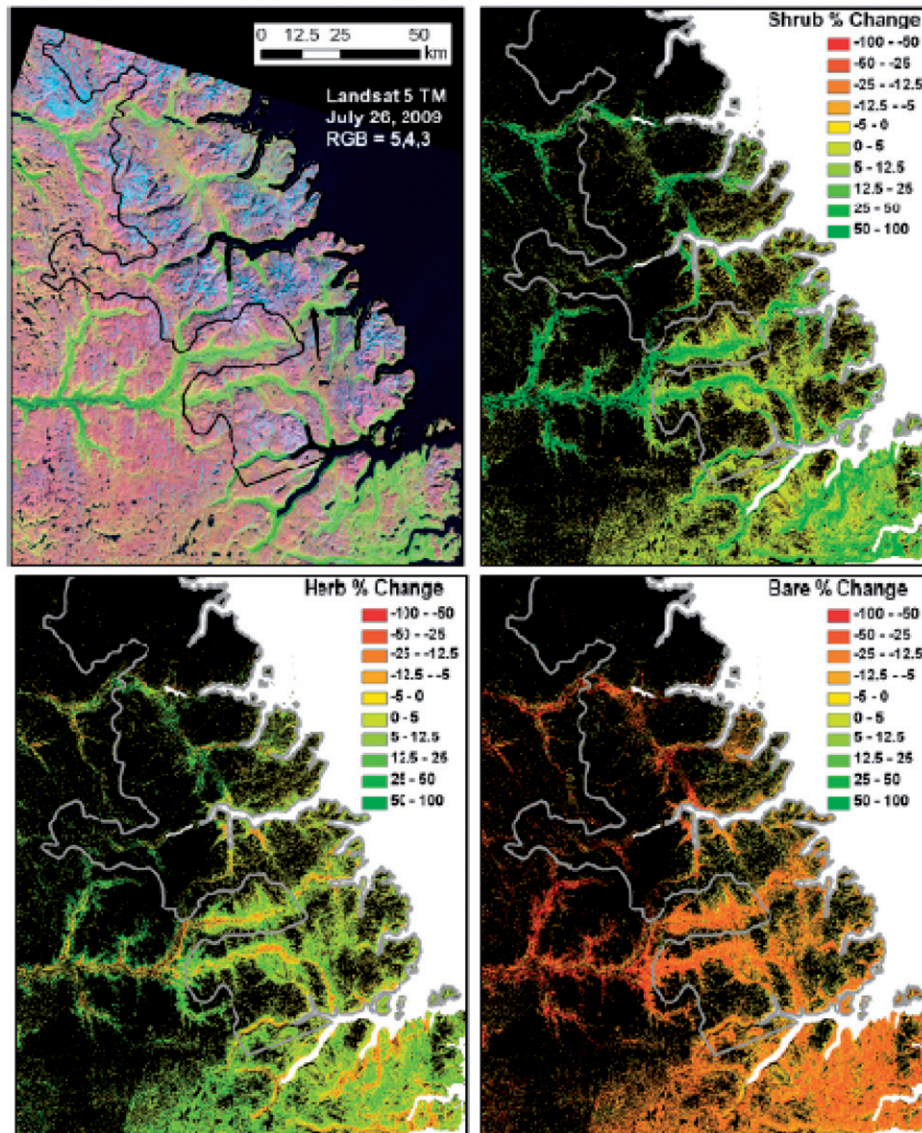


Figure A1. Predicted fractional land cover changes for Torngat Mountains NP. The image in the upper left is a reference Landsat image from 26 July 2009 in which Landsat bands 4, 5, and 6 are displayed as red, green and blue to create a composite false colour image that highlights shrubs in green in the valleys.
Source: Fraser et al. (2011).