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INTRODUCTION

An introduction to Canada's boreal zone: ecosystem processes, health, sustainability, and environmental issues[1]

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Abstract: The boreal zone and its ecosystems provide numerous provisioning, regulating, cultural, and supporting services. Because of its resources and its hydroelectric potential, Canada's boreal zone is important to the country's resource-based economy. The region presently occupied by Canada's boreal zone has experienced dramatic changes during the past 3 million years as the climate cooled and repeated glaciations affected both the biota and the landscape. For about the past 7000 years, climate, fire, insects, diseases, and their interactions have been the most important natural drivers of boreal ecosystem dynamics, including rejuvenation, biogeochemical cycling, maintenance of productivity, and landscape variability. Layered upon natural drivers are changes increasingly caused by people and development and those related to human-caused climate change. Effects of these agents vary spatially and temporally, and, as global population increases, the demands and impacts on ecosystems will likely increase. Understanding how humans directly affect terrestrial and aquatic ecosystems in Canada's boreal zone and how these effects and actions interact with natural disturbance agents is a prerequisite for informed and adaptive decisions about management of natural resources, while maintaining the economy and environment upon which humans depend. This paper reports on the genesis and present condition of the boreal zone and its ecosystems and sets the context for a detailed scientific investigation in subsequent papers published in this journal on several key aspects: carbon in boreal forests; climate change consequences, adaptation, and mitigation; nutrient and elemental cycling; protected areas; status, impacts, and risks of non-native species; factors affecting sustainable timber harvest levels; terrestrial and aquatic biodiversity; and water and wetland resources.

Key words: boreal forest, resource development, disturbances, climate change, ecosystem integrity, resilience.

Résumé : La zone boréale et ses écosystèmes fournissent de nombreux services d'approvisionnement, de régularisation, culturels et de support. Compte tenu de ses ressources et de son potentiel hydroélectrique, la zone boréale du Canada est importante pour son économie basée sur les ressources. La région présentement occupée par la zone boréale canadienne a connu des changements drastiques au cours des derniers 3 millions d'années; un rafraichissement du climat et des glaciations répétées ont affecté à la fois le biote et le paysage. Au cours des 7000 dernières années, le climat, le feu, les insectes, les maladies et leurs interactions ont constitué les forces naturelles les plus importantes derrière la dynamique des écosystèmes boréaux, incluant la rajeunissement, le cyclage biogéochimique, le maintien de la productivité et la variabilité des paysages. Se superposant aux agents naturels, il y a les changements causés par les habitants et le développement ainsi que ceux reliés au changement climatique d'origine anthropique. Les effets de ces agents varient de façon spatio-temporelle et à mesure que la population globale augmente, les demandes et les impacts sur les écosystèmes sont susceptibles d'augmenter. La compréhension de la façon avec laquelle les humains affectent directement les écosystèmes terrestres et aquatiques de la zone boréale du Canada et comment ces effets et ces activités interagissent avec les agents de perturbations naturelles constituent un préalable pour la prise de décisions documentées et adaptatives en aménagement des ressources naturelles, tout en maintenant l'économie et l'environnement dont dépendent les humains. On fait ici état de la genèse et de la condition actuelle de la zone boréale et de ses écosystèmes et établit le contexte pour une recherche scientifique détaillée, présentée dans les autres sujets traités dans ce journal sur plusieurs aspects; carbone dans la forêt boréale; conséquences, mitigation adaptation au changement climatique; cyclage des nutriments et des éléments; aires protégées; état, impacts et risques des espèces adventices; états et moteurs des niveaux de récolte durable; biodiversité terrestre et aquatique; et ressources en eau et terres humides. [Traduit par la Rédaction]

Mots-clés : forêt boréale, développement des ressources, perturbations, changement climatique, intégrité des écosystèmes, résilience.

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1. Introduction

Large areas of the world are subject to overpopulation, disasters, air and water pollution, loss of biological diversity, deforestation, and soil degradation and depletion (Vitousek et al. 1997; Cohen 2003; Jenkins 2003; Stocking 2003; Rockström et al. 2009*b*). With the world's population estimated at 7.1 billion people in July 2013 (CIA 2013), humans are having an enormous impact on the planet's environment and ecosystems, both terrestrial and aquatic (Raven 2002; McMichael et al. 2003; Pauly et al. 2003; Palmer et al. 2004). Global change, which involves ever-increasing human modification of planetary systems, is an important concern (Hassan et al. 2005). Generally, the most severe impacts occur in the world's most heavily populated areas and in some of the poorest nations (WCED 1987). Even the US Central Intelligence Agency, an organization that most would not think would usually concern itself with environmental matters, has stated that "the rapid depletion of nonrenewable mineral resources, the depletion of forest areas and wetlands, the extinction of animal and plant species, and the deterioration in air and water quality pose serious long-term problems", which the governments of the world are only beginning to address (CIA 2013). Researchers, particularly those in the biological sciences, have been keenly aware of these global environmental challenges for decades and have long advocated discussion of these pressing issues in political spheres, in the hope that governments would act to solve the threats to human survival (Hassan et al. 2005). However, other influences, such as economics, poverty, and national security, have generally taken precedence over concerns for the environment. Globally, this trend must change because, ultimately, our individual security and that of our global society, not to mention human survival, depend on our ability to obtain adequate food and clean water and to maintain a livable climate (McMichael 1997; Rapport et al. 1998).

The world's forests cover about 30% (3.9 billion ha) of the world's terrestrial area in four major biomes: tropical, subtropical, temperate, and boreal (FAO 2001). These forests are important sources of renewable goods and services for humans, and they hold much of the world's biodiversity. Among these biomes, the boreal zone is the most northerly and represents one of the largest biogeoclimatic areas, encompassing a variety of climates, surficial geologies, soils, wetlands and aquatic systems, and vegetation assemblages that have coevolved since the end of the last continental glaciation (Fig. 1). Brandt (2009) defined the boreal zone as the broad, circumpolar vegetation zone of high northern latitudes covered principally with forests and other wooded land consisting of cold-tolerant tree species primarily within the genera *Abies*, *Larix*, *Picea*, or *Pinus* but also *Populus* and *Betula*; the zone also includes lakes, rivers, and wetlands, and naturally treeless areas such as alpine areas on mountains, heathlands in areas influenced by oceanic climatic conditions, and some grasslands in drier areas. In contrast, the temperate zone is defined by the dominance on most sites of tree species intolerant of extremely cold winter temperatures, or grasslands in the interior of continents where their occurrence is dictated more by moisture availability (Brandt 2009). The hemiboreal subzone is defined by the co-occurrence of cold-intolerant tree species, cold-tolerant tree species, and species with intermediate cold-tolerance, with the cold-tolerant species contributing substantially to the forest cover; Brandt (2009) includes the latter subzone in the temperate zone. Larsen (1980), Hytteborn et al. (2005), and Weber and Van Cleve (2005) have previously provided thorough reviews of the climate, ecology, floristics, and history of the boreal zone. Globally, the boreal zone covers about 1.890 billion ha in the northern hemisphere, 60% in Russia, 28% in Canada, and the remainder divided among 10 other countries, although there are differences in total area depending on the study (Table 1). In Canada, the boreal zone covers 552 million ha, of which 270 million ha supports forests, 39 million ha supports other wooded land, 171 million ha is other land, and 71 million ha is covered by lakes, ponds, and rivers (Table 2)[2]. About 96% (532 million ha) of the boreal zone in Canada is either federal, provincial, territorial, or Aboriginal lands, and a small percentage of the land is privately owned (Table 3). About 45 million ha, or 8%, is protected to various degrees within national and provincial parks, wilderness reserves, and other protected areas (Andrew et al., In press).

The boreal zone and its ecosystems provide numerous goods and services, including provisioning (timber, pulp, fuelwood, food, and fresh water), regulating (climate regulation, flood regulation, disease regulation, and water purification), cultural (spiritual, educational, recreational, and aesthetics), and supporting (primary production, nutrient cycling, and soil formation) (Hassan et al. 2005). Canada's boreal zone is important to the country's resource-based economy because of its renewable forest resources, nonrenewable mineral and energy resources, and hydroelectric production and potential (Bogdanski 2008). Although the circumboreal zone has previously been considered relatively pristine and free of industrial development because of its remoteness, exponential world population growth has brought increasing pressures to bear.

The most important natural drivers of boreal ecosystem dynamics are climate, fire, insects, diseases, and their interactions. For several thousand years, these natural disturbances have played an important role in the rejuvenation of boreal ecosystems, in biogeochemical cycling and maintenance of productivity, and in landscape variability in terms of species composition, ecosystem size, and successional stage. Thus, boreal ecosystems are not static, but rather are in flux across the landscape, because they are affected by various intrinsic and extrinsic factors operating at various spatial and temporal scales. Sustainable resource management, therefore, depends not only on knowledge of the current state of these ecosystems but also on knowledge of the historical range in natural variability associated with ecosystem characteristics at different scales. Layered upon natural drivers of change are changes caused by people and development and those related to human-caused climate change (Hassan et al. 2005; IPCC 2007*a*). The latter effects also vary spatially and temporally, and, as global population increases, the demands and impacts on ecosystems will increase. A thorough understanding of how humans are affecting terrestrial and aquatic ecosystems in Canada's boreal zone is required to make informed and adaptive decisions about the management of natural renewable and nonrenewable resources, while maintaining the economy and the environment upon which human lives depend (e.g., Brundtland 1997). This paper reports the overall genesis and present condition of Canada's boreal zone and sets the context for a scientific investigation and review in subsequent papers in this journal on several key aspects: carbon in boreal forests (Kurz et al. 2013); climate change consequences, adaptation, and mitigation (Price et al. 2013; Gauthier et al., Manuscript in preparation; Lemprière et al. 2013, respectively); nutrient and elemental cycling (Maynard et al., In press); protected areas (Andrew et al., In press); status, impacts, and risks of non-native species (Langor et al., Manuscript in preparation); factors affecting sustainable timber harvest levels (Lavigne et al., Manuscript in preparation); terrestrial and aquatic biodiversity (Venier et al., Manuscript in preparation; Kreutzweiser et al. 2013, respectively); and water and wetland resources (Webster et al., Manuscript in preparation).

[2]Forest and other wooded land area differ from Brandt (2009) because more recent inventory data were accessed for this paper.

Fig. 1. Distribution of the circumboreal zone (Eurasia based on Lavrenko and Sochava 1954, Ahti et al. 1968, Denisov 1970, and Kurnaev 1990; North America is that of Brandt 2009).

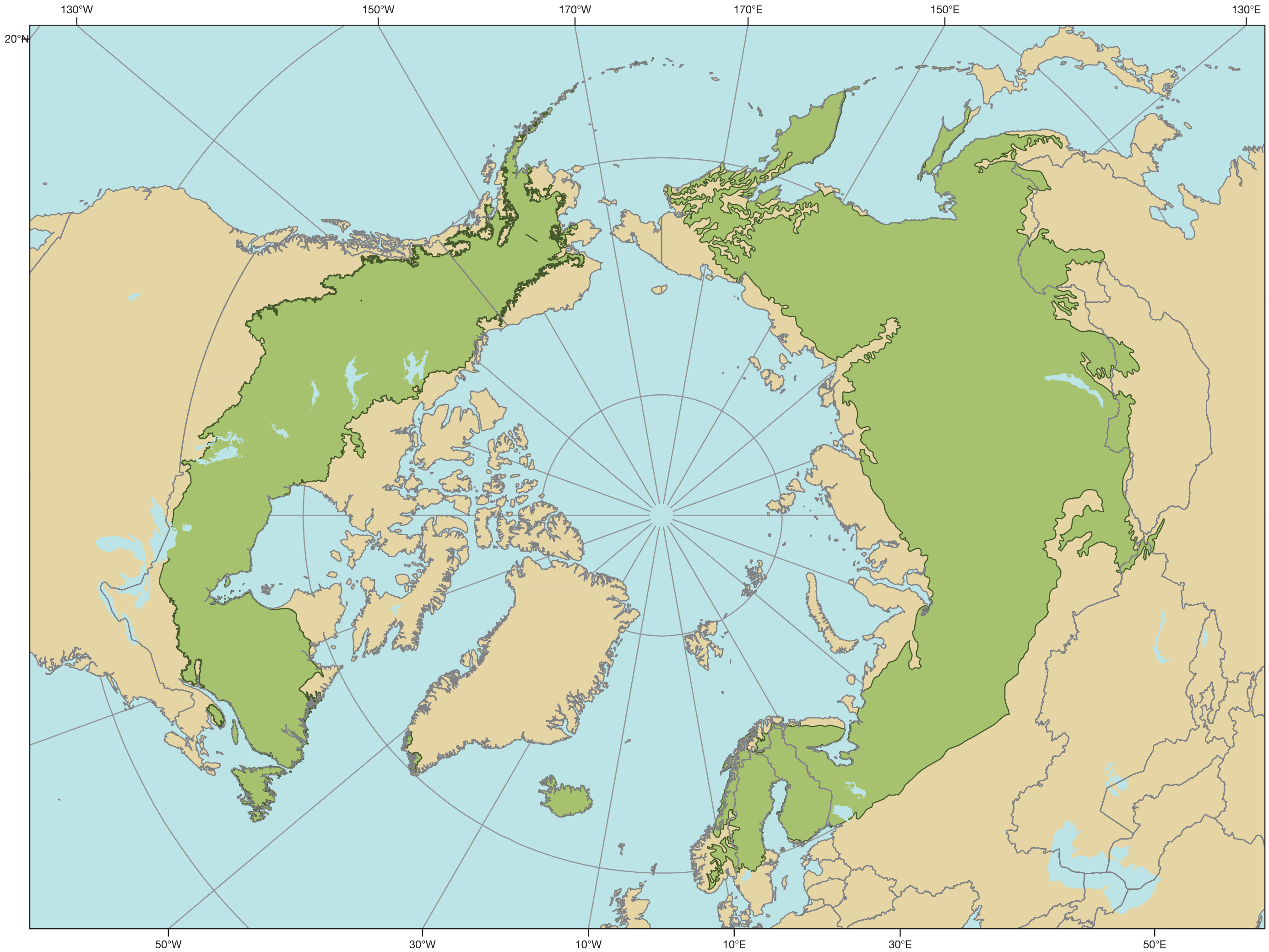


Table 1. Total area (in millions of hectares) of the boreal zone in various countries, based on this paper's map (as depicted in Fig. 1) and maps from several studies dealing with North America, Eurasia, or regions therein. Studies are listed in reverse chronological order.

Study[a]	Canada	China	Finland	Greenland	Iceland	Kazakhstan	Mongolia	Norway	Russia	Saint Pierre and Miquelon (Fr.)	Sweden	United States	Total
Lavrenko and Sochava (1954)		29.4	29.5			2.0	14.9	13.4	1016.1		25.9		
Hou et al. (1956)		21.2											
Hustich (1960)			31.3					10.8			26.4		
Sjörs (1963)			32.5					18.6			28.7		
Ahti et al. (1968)			32.4					10.3			28.6		
Wolfe (1979)		21.7											
Tuhkanen (1984)		5.0	31.1		9.7	0.3		22.4	1105.2		29.1		
Belov et al. (1990)						1.9	0.1		979.4				
Kurnaev (1990)						2.2	0.7		870.5				
Finch (1999)							7.8						
Moen (1999)								17.9					
FAO (2001)	525.7	15.9	32.7		10.1	0.7	10.8	29.9	1149.9		31.4	69.7	
Olson et al. (2001)	461.1	0.3	32.6		9.1		3.8	9.7	917.5		26.0	49.7	
Brandt (2009)	552.0			1.6						0.0		73.7	
Ave. of above papers	512.9	15.6	31.7	1.6	9.6	1.4	6.4	16.6	1006.4	0.0	28.0	64.4	1694.7
Min. of above papers	461.1	0.3	29.5	1.6	9.1	0.3	0.1	9.7	870.5	0.0	25.9	49.7	1457.7
Max. of above papers	552.0	29.4	32.7	1.6	10.1	2.2	14.9	29.9	1149.9	0.0	31.4	73.7	1927.8
This paper	552.0	26.0	32.5	1.6	10.3	2.1	13.4	14.8	1133.0	0.0	30.5	73.7	1889.9

Notes: Method of determining areas adapted from methods described by Brandt (2009). Maps were projected using the North Polar equal-area projection. The reference layer was from the Environmental Systems Research Institute (1 : 1 000 000) (Esri 2012).

Table 2. Areal extent (in thousands of hectares) of the North American boreal zone.

	National				Boreal zone				
Nation	Total area	Land area	Inland water	Forest and other wooded land	Total area	Forest land	Other wooded land	Other land	Water
Canada	997 969[a]	908 711[a]	89 258[a]	392 178[a]	551 982[a]	270 418[a]	38 755[a]	171 471[a]	71 339[a]
Greenland	216 609[b]	40 650[b]	395[b]	8[c]	1595[d]	0[c]	8[c]	1570[e]	15
Saint Pierre and Miquelon (France)	23[f]	22	1[c]	3[c]	23[d]	3[c]	0[c]	20[c]	1[c]
United States	982 668[g]	916 197[gh]	66 471[g]	303 208[i]	73 701[d]	47 324[e]	7456[e]	17 971[e]	1282[j]
Column total	2 197 269	1 865 580	156 125	695 397	627 301	317 745	46 219	191 032	72 637

Note: Adapted from Brandt 2009 using Canada's National Forest Inventory (NFI 2013).

[a]Intersection of the boreal zone (Brandt 2009) and Canada's National Forest Inventory (NFI 2013).

[b]From Weng (1995), who used a 1 : 2 500 000 map of Greenland and the Sanson–Flamsteed equivalent projection.

[c]From FAO (2006).

[d]This value is not the total of areas reported for forest land, other wooded land, nonforest land, and water because it was determined independently of the latter four areas using a GIS and the boreal zone map projected with Albers equal-area conic projection and standard parallels set at 47.5°N and 54.5°N.

[e]Determined using a GIS by intersecting the boreal zone map (Brandt 2009) and forest type coverage developed as part of the Global Forest Resources Assessment in 2000. The latter forest type coverage is available at the U.S. Geological Survey's Global Land Cover Characterization website (http://edc2.usgs.gov/glcc/glcc.php).

[f]Determined using a GIS and the ESRI 1 : 1 000 000 Map of the World (Esri 2012) projected with Albers equal-area conic projection and standard parallels set at 47.5°N and 54.5°N.

[g]From the World Factbook (CIA 2013).

[h]The difference between the value in this table and that reported by Smith et al. (2004; 2 263 230 000 acres or 915 917 000 ha) is probably due to rounding errors in the conversion from acres to hectares (i.e., 1 ha = 2.471 acres).

[i]From Smith et al. (2004).

[j]Determined using a GIS by intersecting the boreal zone map and the 1 : 2 000 000 hydrology coverage from the *National Atlas of the United States* (U.S. Department of the Interior 2008).

Table 3. Land ownership within Canada's boreal zone.

	Ownership							
	Federal	Provincial	Territorial	Municipal	Aboriginal	Private	Other[a]	Total
Forest	4189	207 449	46 800	655	7223	3111	991	270 418
Other wooded land and other land	4457	113 179	69 320	1016	8053	9189	5012	210 226
Water	1516	47 243	19 020	206	2008	394	951	71 388
Total	10 162	367 870	135 140	1877	17 284	12 694	6954	551 982

Note: Source: Canada's National Forest Inventory (NFI 2013).

[a]Missing information.

2. Canada's boreal zone: past and present

2.1. The Quaternary

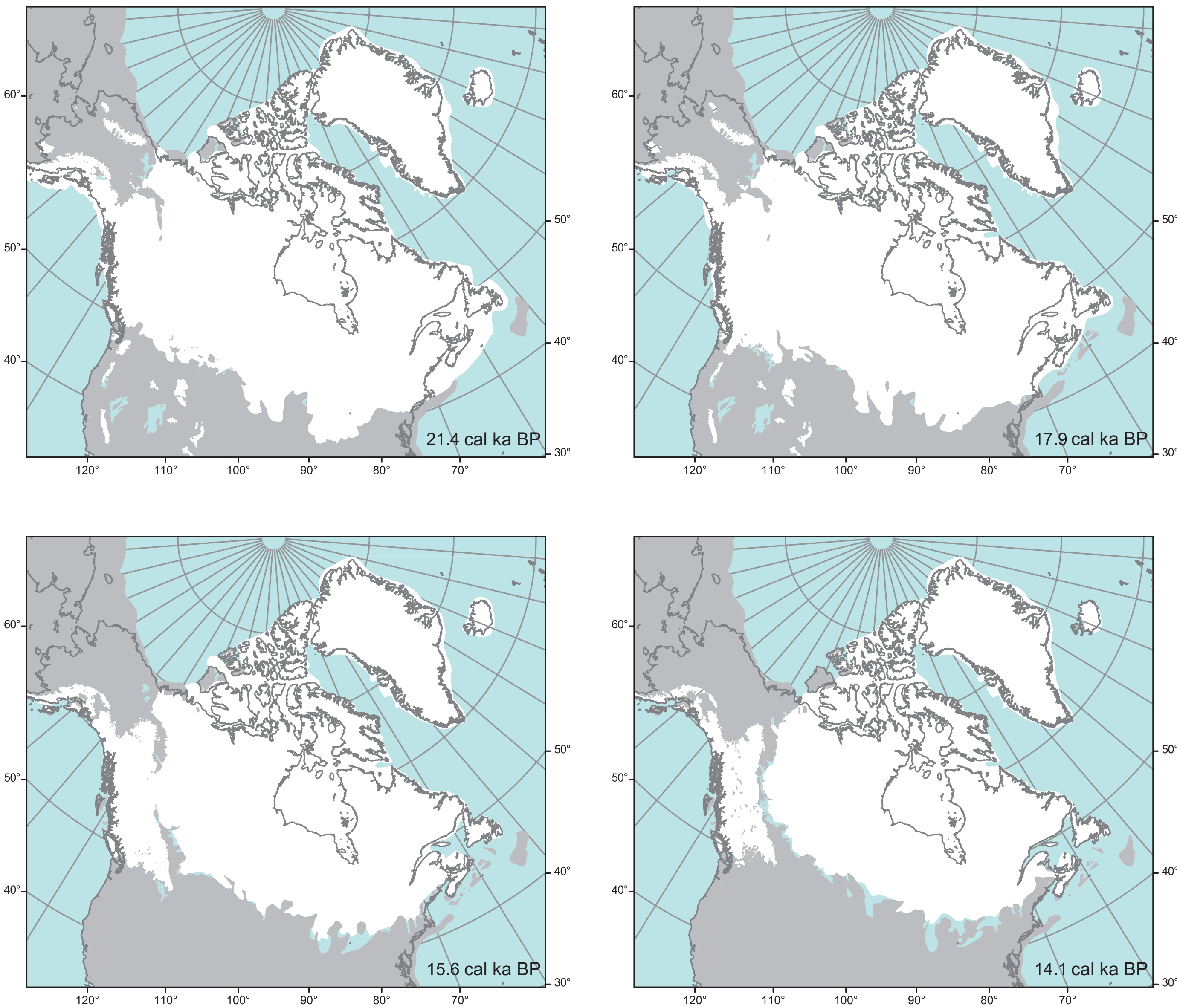
The region presently occupied by Canada's boreal zone has experienced dramatic changes during the past 3 million years. During the Quaternary, major glacial cycles in the northern hemisphere began to affect this region about 2.7 million years ago (Shackleton et al. 1984; Balco et al. 2005; Herbert et al. 2010). Between 2.7 million and 1 million years ago, 35–40 glacial cycles occurred, one about every 41 kyr (Muller and MacDonald 2000; Herbert et al. 2010). In the past 1 million years, there have been about nine glacial cycles, about once every 100 kyr (Erickson 1990; Herbert et al. 2010).

Climate variability causes the world's vegetation to change at centennial, millennial, and longer time scales. We know little about the vegetation that existed during previous interglacial periods in the area currently occupied by the boreal zone. Since the most recent glacial maximum, ecosystem development has varied across North America as a function of the timing of deglaciation (Fig. 2) and latitudinal position (Ritchie 1987; Dyke et al. 2003; Dyke 2004). Plant species reacted to changes in climate as individual taxa (Ritchie 1987; Huntley and Webb 1988; Prentice 1992; Jackson et al. 1997), which resulted in a variety of plant associations at different points during the past 21 000 years that have no floristic analogues today (Overpeck et al. 1992; Williams et al. 2004). Vegetation development since the most recent glacial maximum can be divided into a full-glacial stage between 21 000 and 17 000 years ago, when vegetation development was relatively stable; a transitional stage during the late glacial (16 000 – 11 500 years ago) and the early Holocene (11 500 – 8000 years ago); and a return to relative stability during the mid to late Holocene (7000 – 500 years ago) (Williams et al. 2004).

Coniferous trees such as *Picea glauca*, *Picea mariana*, *Larix laricina*, *Abies balsamea*, and *Pinus banksiana* dominate the Canadian boreal zone but large areas are also covered by shade-intolerant deciduous trees such as *Populus tremuloides*, *Populus balsamifera*, and *Betula papyrifera*, either in pure stands or, more commonly, intermixed with conifers. In the western boreal zone, *Pinus contorta* var. *latifolia* and *Abies lasiocarpa* cover extensive areas. Forests in which *Picea* is the leading genus comprise 65% of the forest area of the boreal zone; values for *Larix*, *Abies*, *Pinus*, and *Populus* are 2%, 3%, 7%, and 12%, respectively (NFI 2013).

Human impacts in the boreal zone are confined to the Holocene. Archeological, genetic, and geological evidence suggests that it was between 14 000 and 13 500 years ago, as the continental glaciers receded and coastal areas of northwestern North America became ice-free, that humans, who had previously settled in Beringia (Tamm et al. 2007), first started moving southward and settling along Pacific coastal areas of the Americas before migrating and settling inland (Dixon 2001; Schurr and Sherry 2004; Fagundes et al. 2008; Goebel et al. 2008). Human populations in North America originated from a founding population of 2000 individuals or fewer (Fagundes et al. 2008; Mulligan et al. 2008). Genetic and archeological evidence also exists for subsequent Eskimo–Aleut and Na–Dené dispersal events from northeast Asia into northern North America (Schurr and Sherry 2004; Goebel et al. 2008). The most recent major migration event began in

Fig. 2. Deglaciation in North America from the last glacial maximum at 21 400 – 6300 calendar years BP (adapted from Dyke et al. 2003).



earnest about 500 years ago and involved peoples primarily from Europe and Africa, who moved across the Atlantic Ocean after Christopher Columbus "rediscovered" the New World. Although the number of people in North America before 1492 is highly contested (Dobyns 1966; Thornton 1987), recent estimates, based on critical reviews by Thornton (1987, 1997), are more than 7 million for North America as a whole and more than 2 million for Canada. After 1492, introduced diseases of European and African origin, warfare, and displacement dramatically reduced the populations of Aboriginal peoples in North America, with a nadir of about 375 000 occurring around 1900 (Dobyns 1966, 1983, 1993; Thornton 1987). In Canada in the same year, the Aboriginal population was 126 000 (Ministère du Commerce du Canada 1950) and the non-Aboriginal population was about 5.2 million (Urquhart and Buckley 1965).

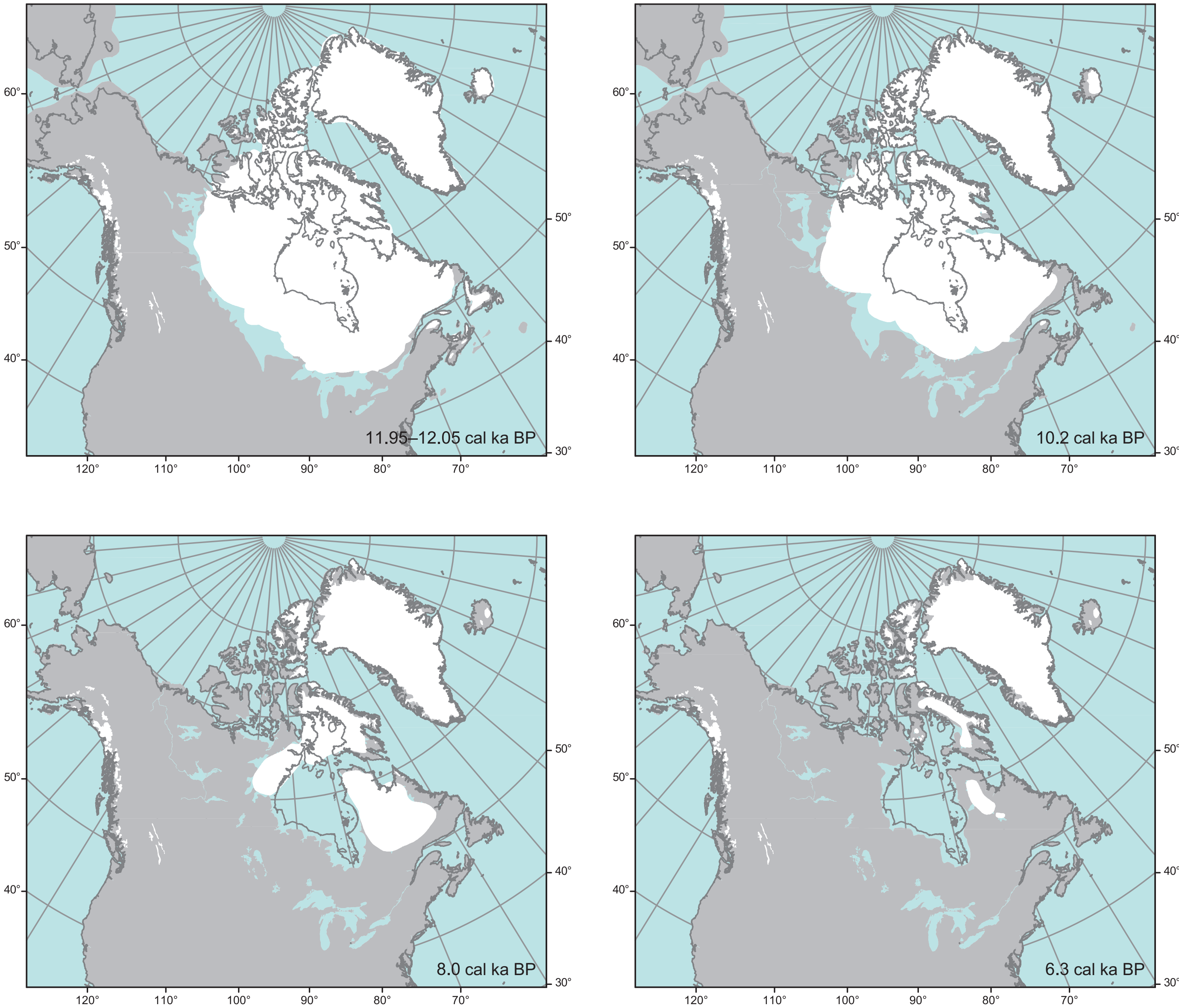
Between 12 000 and 10 000 years ago, as the last continental glaciation waned, 34 Pleistocene genera of mammalian megafauna became extinct within North America (Koch and Barnosky 2006; Faith and Surovell 2009). It is most likely that humans, both directly via hunting and indirectly via competition and habitat changes, precipitated these extinctions, which were paced both spatially and temporally by changing climate (Barnosky et al. 2004; Burney and Flannery 2005; Koch and Barnosky 2006; Gillespie 2008; Faith and Surovell 2009), although the exact causes for certain species is still the subject of debate (e.g., woolly mammoth, see Palkopoulou et al. 2013). Extinctions of large herbivores may have triggered the loss of open vegetation and habitat mosaics, the decline of plants that had coevolved with the animals, and an increase in the incidence of fire (Gill et al. 2009; Johnson 2009). Although these changes were likely dramatic, few Quaternary plant extinctions have been documented (Tralau 1959; Leopold 1967; van der Hammen et al. 1971; Godwin 1975; Watts 1988; Willis and Niklas 2004), with only one (that of *Picea critchfieldii*) confirmed as occurring in the late Quaternary (Jackson and Weng 1999).

2.2. Drivers of change during the late Holocene

2.2.1. Climate

The climate of the boreal zone is characterized by cool short summers, cold long winters, large annual ranges in temperature, and modest amounts of precipitation concentrated in summer. It

Fig. 2 (*concluded*).



is strongly continental, except in coastal areas, which explains the large differences in temperature between winter and summer. Also, day length, and thus photoperiod, is long during summer because of the high latitudes of this zone.

Climate and forest ecosystems are intimately linked (Woodward 1987), and this linkage is dynamic, because climate is constantly changing. Climate and weather influence the structure and functioning of ecosystems of the boreal zone both directly, through such features as temperature and precipitation, and indirectly, through disturbance by wind and snow and through permafrost (Brown and Péwé 1973; Walter 1973; Woodward 1987; Kneeshaw and Bergeron 1998; McCarthy 2001). The factors that control climate include variation in solar radiation relative to latitude, distribution of continents and oceans, atmospheric pressure and wind systems, ocean currents, major features of the terrain, proximity to bodies of water, and local features (Trewartha and Horn 1980). Boreal trees have lower productivity but greater cold hardiness (Woodward 1987) than trees of temperate forests (Arris and Eagleson 1994). Thus, the poleward limit for any given tree species is probably defined by temperature, whereas the equatorial limit is probably defined by competitive exclusion (Woodward 1987). As climate changes, the corresponding weather variables also change. Traditionally, both in research studies and in the documentation of climate, much of the focus has been on changes in mean temperature. However, extremes in weather (i.e., ≥1 standard deviation from the mean) are probably more important than so-called climate normals in determining the distribution of plants (Daubenmire 1956; George et al. 1974; Sakai 1983; Sakai and Larcher 1987; Brandt et al. 2004). For example, unusually late frosts in spring or early summer can severely damage buds, seedlings, or flowers. Such frosts may also be harmful to the production of viable seeds and may thereby limit the range of a species (e.g., Black and Bliss 1980). Similar principles apply to extremes in precipitation, wind, and drought, all of which affect plant species. Furthermore, the distribution of vegetation results from the interaction of climate with many other factors, such as physical geography (topography, soil nutrients, and drainage), past history, disturbance (natural and anthropogenic), herbivory, and competition (both among plants and among the animals that constitute the community). Climatic influences on fire and insect disturbances, disease, and soil properties such as permafrost further serve to determine the character and vegetation of a region.

As a result of variable climate across such a large area as Canada, the boreal zone is not uniform from east to west or south to north. Moving from east to west, there is a clear moisture gradient with areas close to the coasts having higher levels than interior continental areas. Moving from south to north, the boreal zone changes along a temperature gradient from closed forest to open forest to a forest–tundra landscape. The other major processes, fire, insects, and disease, that drive boreal ecosystems also differ in their frequency and intensity along these two gradients.

2.2.2. Fire

Continuous fire activity during the past several hundred years has largely shaped current forests, although insects (see below) have had a major role at times. Fire is the major stand-renewing agent for much of the Canadian boreal zone, and it plays an essential role in boreal ecosystems by regulating the effects of insects and diseases and by influencing species composition, age structure, productivity, and biodiversity (Weber and Flannigan 1997). Fire activity before European contact included lightning-caused fires and fires used by Aboriginal peoples (Pyne 2008). Although lightning is the cause of only 35% of present forest fires in Canada, these fires are responsible for about 85% of the total area burned (Weber and Stocks 1998). There is great year-to-year variability in annual area burned in Canada (Stocks et al. 2003), and fire activity is strongly influenced by four factors: weather and climate, fuels, ignition agents, and humans (Flannigan et al. 2005). In the boreal zone, weather and climate constitute the most important natural factors influencing forest fires (Flannigan and Wotton 2001; Hely et al. 2001). In particular, weather determines fuel moisture, influences lightning ignitions, and contributes to the rate of fire growth. High-intensity crown fires are mainly responsible for the renewal of stands (Weber and Stocks 1998; Stocks et al. 2003).

2.2.3. Insects and diseases

Insects and diseases play important roles as disturbance agents in boreal forest ecosystems, in particular by regulating primary productivity through effects on the structure and composition of forest stands (Mattson and Addy 1975; McCarthy 2001). Most of our knowledge about past insect and disease outbreaks relies heavily on dendrochronological techniques and longer-term data sets generated by other methods (e.g., Royama 1984; Volney 1988; Burleigh et al. 2002; Jardon et al. 2003). Because of their dependence on their tree hosts, insects and diseases most likely have responded individually to climatic changes that have in turn affected tree species distributions during the Holocene (Mathews 1979). The roles of these agents in determining the character of forest vegetation is further complicated by the complex interactions of insect and disease cycles with fire and climate (Volney 1988; Fleming and Volney 1995).

Four outbreak insect species periodically defoliate several million hectares of susceptible host forest species (Prebble 1975; Armstrong and Ives 1995). This defoliation suppresses growth in the affected host trees and may kill trees if the outbreak persists for several years (see also Lavigne et al., Manuscript in preparation). Spruce budworm (*Choristoneura fumiferana*) and jack pine budworm (*Choristoneura pinus pinus*) are the principal insect defoliators in boreal coniferous forests, whereas forest tent caterpillar (*Malacosoma disstria*) and large aspen tortrix (*Choristoneura conflictana*) are the principal insect herbivores of trembling aspen (*Populus tremuloides*) forests of the boreal zone (Ives and Wong 1988; Rose and Linquist 1994, 1997; Armstrong and Ives 1995; Rose et al. 1999). Stands of spruce, fir, jack pine, and trembling aspen, the common hosts of the latter four defoliators, constitute about 87% of the forest area of the boreal zone and more than 90% of the timber volume (NFI 2013), although insect populations in northern areas of the boreal zone do not typically reach outbreak status. Diseases can also be primary pests causing diminished growth and tree death, but more often they are of a secondary nature (affecting trees following the weakening of the host by another damage agent), causing root and trunk rots. Important conifer diseases include the parasitic plant, lodgepole pine dwarf mistletoe (*Arceuthobium americanum*), and Armillaria root disease (*Armillaria* spp.). Rots of conifers include *Onnia tomentosa* ([equiv.] *Inonotus tomentosus*, *Polyporus tomentosus*), *Pholiota alnicola*, *Scytinostroma galactinum*, *Coniophora puteana*, *Porodaedalea pini* ([equiv.] *Phellinus pini*, *Fomes pini*), and *Haematostereum sanguinolentum* (Hiratsuka 1987; Myren 1994; Brandt 1995; Fox 2000). On boreal hardwood trees (mainly trembling aspen), hypoxylon canker (*Entoleuca mammata*) and Armillaria root disease are important (Hiratsuka 1987; Myren 1994; Brandt et al. 2003; Ostry and Anderson 2009). Principal decays of these hardwoods are caused by fungi such as *Phellinus tremulae*, *Peniophora polygonia*, *Radulodon americanus*, *Gymnopilus spectabilis* ([equiv.] *Pholiota spectabilis*), and *Hemipholiota populnea* ([equiv.] *Hemipholiota destruens*, *Pholiota destruens*) (Hiratsuka 1987; Myren 1994; Brandt 1995; Brandt et al. 2003).

2.2.4. Aboriginal forest use

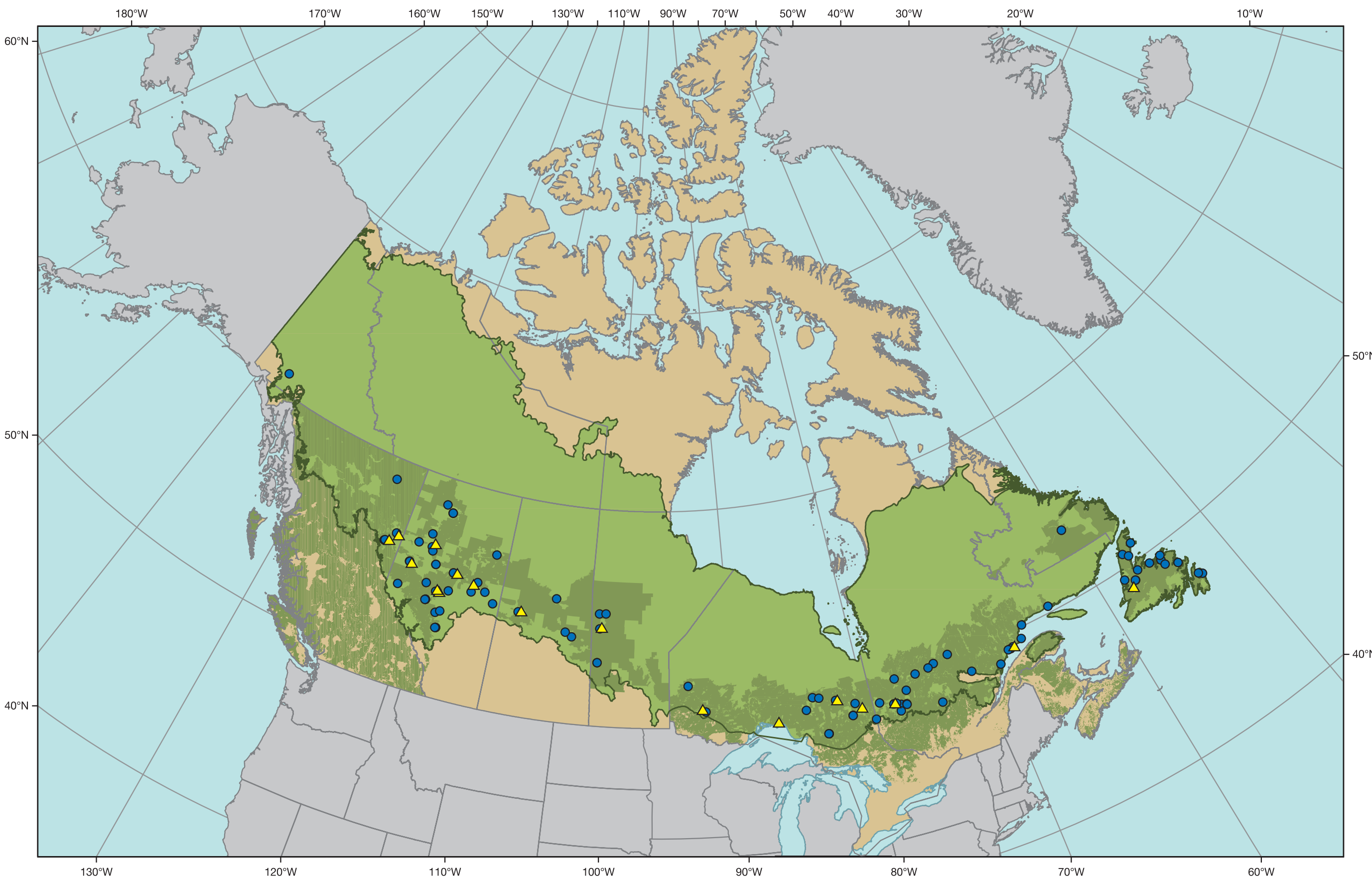
The area currently occupied by the boreal zone has been used by Aboriginal peoples for thousands of years (Helmer et al. 1977; Helm 1981; Gordon 1996). Aboriginal peoples originally followed subsistence hunter–gather lifestyles, and agriculture was not practiced in the boreal zone (Cleland 1966). Limited amounts of wood were used for shelters, canoes, traps and snares, fuel, and some tools (Rogers and Leacock 1981; Rogers and Smith 1981). The diet of Aboriginal peoples in the boreal zone included all ungulate species and several other common boreal animals such as fish, waterfowl, bear, beavers, muskrats, and porcupines (Gillespie 1981; Rogers and Leacock 1981; Rogers and Smith 1981; Rogers 1983; Winterhalder 1983). Animal hides were used for clothing, bedding, and shelters, and animal bones were used for some tools (Clark 1981; Noble 1981; Rogers and Smith 1981; Wright 1981).

Aboriginal populations declined rapidly after 1492. Subsistence on prey species continued, but access to European guns and metals (used for arrow and spear tips, knives, and axes), afforded by the fur trade that was developing with the Europeans (i.e., through the Hudson's Bay Company and the North West Company), began to change the means by which Aboriginal peoples hunted their prey (Clark 1981; Helm et al. 1981; Rogers 1983; Hanks and Pokotylo 2000). Settlement patterns of Aboriginal peoples changed as populations began to concentrate around trading posts and became more dependent on European supplies, especially when food animals were scarce in the forests of the boreal zone (Helm et al. 1981; Hanks and Pokotylo 2000). These changes had a influence on boreal forest vegetation, as Aboriginal peoples' sophisticated understanding of fire was no longer being applied in managing vegetation and wildlife populations in the boreal ecosystems of Canada (Lewis 1977). The annual use of fire to create local openings for large ungulates had previously kept the forest in check, but this practice was increasingly abandoned following European contact and settlement (Campbell and McAndrews 1995; Clark and Royall 1995).

2.3. The Anthropocene

The Anthropocene, a concept denoting the current interval of time in which many key biogeochemical processes are dominated by humans, emerged with the dawning of the industrial revolution (Crutzen 2002; Zalasiewicz et al. 2010, 2011). Evidence suggests that human actions now constitute the main driver of global environmental change (Rockström et al. 2009*a*). In Canada's boreal zone, much of this activity is related to forestry, extraction of mineral and energy resources, hydroelectric development, and some limited agricultural development and peat mining. Associ-

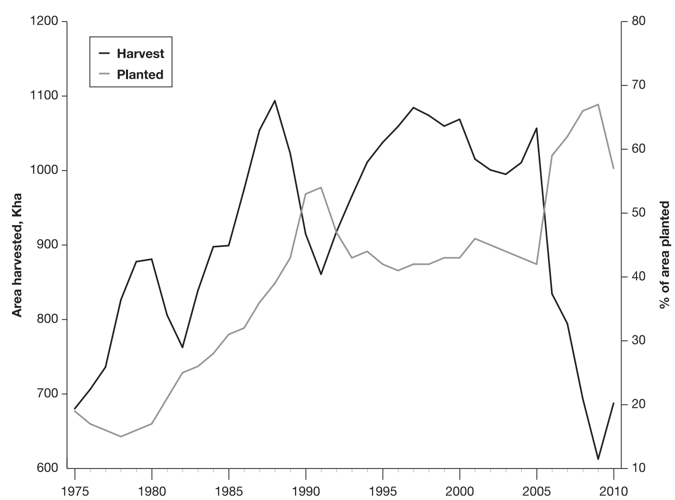
Fig. 3. Canada's commercial forest (dark green), and sawmills (blue circles) and pulp and paper mills (yellow triangles) within Canada's boreal zone (light green).



ated with each of these industrial sectors is the development of infrastructure: roads, railways, pipelines, seismic lines, utility corridors, impoundments, and urban centres of various sizes. Climate change impacts are also evident in Canada's boreal zone (Soja et al. 2006), but they are comparatively recent.

Much of Canada's timber and pulp and paper products for domestic and export markets come from forestry operations in the southern portion of the boreal zone. This region, commonly referred to as the commercial forest, also extends into the temperate zone (Fig. 3). In the boreal portion of the commercial forest, which covers about 144 million ha (R. Brett, personal communication, September 2012), there were about 102 sawmills and 17 pulp and paper mills in 2011 (J. Brandt, unpublished data). There are also 10 closed or decommissioned pulp and paper mills in the boreal zone. Typically, forests are clear-cut with mechanical harvesters, although other silvicultural systems are increasingly used in the boreal zone, depending on local circumstances, including variable retention practices (Sougavinski and Doyon 2002; Serrouya and D'Eon 2004). Cut areas may be prepared mechanically or with prescribed fire before regeneration. Many clearcuts are regenerated artificially by seeding or by planting of seedlings while others are left to regenerate naturally. Although boreal specific data are generally not readily available, many forestry statistics for the boreal zone show similar trends to those of national statistics. Thus, Fig. 4 depicts the proportion of the harvested area planted between 1975 and 2010 nationally. The area of mechanical or chemical stand-tending operations (i.e., mechanical, manual, and chemical release; thinnings; fertilization; other treatments) declined in Canada between 1990 and 2010 but still occurred on more than 200 000 ha in 2010 (National Forestry Database, October 2012). Industrial forestry has a longer history in

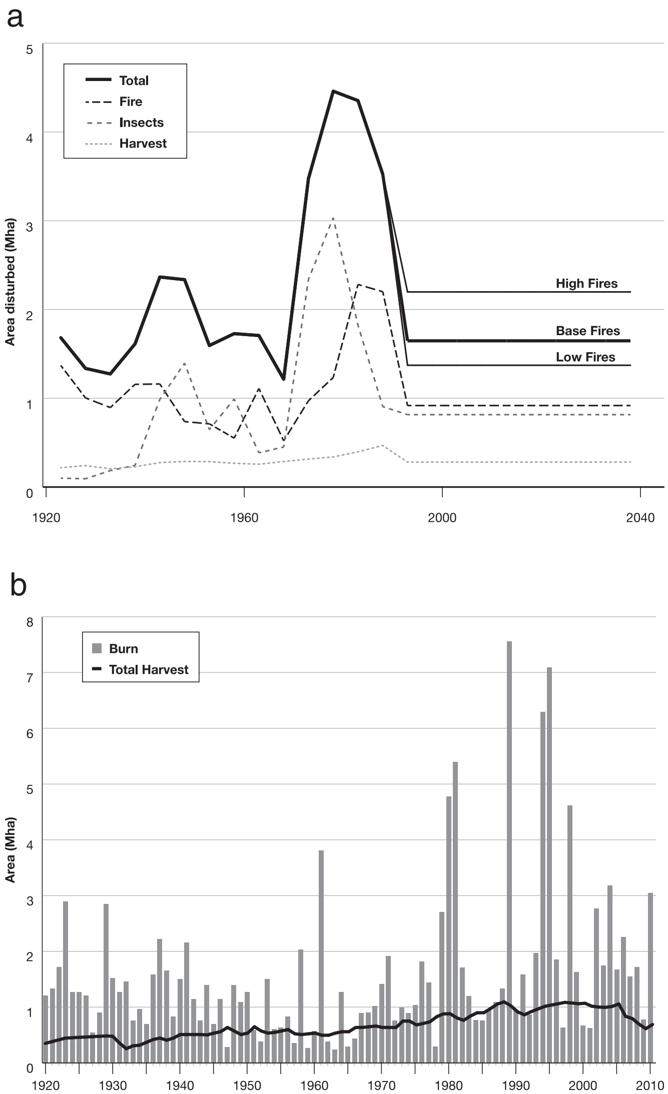
Fig. 4. Annual area clearcut harvested and percent of harvested areas planted in Canada (1975–2010). (Source: National Forestry Database 2011)



the eastern boreal regions of Newfoundland, Ontario, and Quebec, where it began in the first few decades of the 20th century, than in western Canada, where it began in the late 1950s. Area harvested nationally is far lower than the area disturbed by insects or fire, and this trend would be similar for the boreal zone and is projected to continue to 2040 (Fig. 5).

As a result of past mining activity there are more than 10 000 sites across Canada where some form of mining exploration or

Fig. 5. (*a*) Area affected by fire, insects, and tree harvesting from 1920 and projected to 2040 for the boreal forest (from Kurz and Apps 1995). (*b*) Total forest area annually harvested and burned in Canada (1920–2005). Individual fires >20 000 ha in size account for the majority of the average area burned (Stocks et al. 2003). (Sources: NRCan 1994; Macias Fauria and Johnson 2008; National Forestry Database 2011).



activity has taken place, requiring various degrees of rehabilitation (Tremblay and Hogan 2006). Mining in the boreal zone includes extraction of primarily minerals and metals, mostly from the Canadian Shield, extraction of coal and processing of oil sands in the western sedimentary basin southwest of the Canadian Shield, pits and quarries for aggregates, and some mining of peat in peatlands. As of 2009, there were 99 active mineral and metal mines, six smelters, and nine coal mines in the boreal zone (Fig. 6; NRCAN 2009; for oil sands mining, see next section). Mining in the boreal zone began in the latter part of the 19th century, with the rate of new development of mines peaking in the 1930s (Fig. 7; J. Brandt, unpublished data). In the boreal zone, there are at least 1300 former mineral and metal mines[3], not all of which have been reclaimed or remediated (J. Brandt, unpublished data). Mines can be either underground (with access to the mineral deposit via a shaft) or open pit. Tailings (residue left over after the valuable minerals have been extracted) associated with most mines are usually left on the surface adjacent to the mine, and require some form of reclamation. Although boreal-specific information is unavailable, there are more than 41 000 ha of mine tailings in Canada (Feasby and Jones 1994).

Oil and gas exploration and extraction are widespread in the western sedimentary basin of the western boreal zone. Most of the exploration and extraction has occurred since about 1950, although activities associated with this sector have taken place since the late 19th century (Fig. 8). Seismic lines, roads, well sites, pipelines, and related structures are the other main types of development in the oil and gas sector. In the boreal zone as of 2011, there were about 222 000 active and abandoned well sites, mostly in the western boreal zone (Divestco Inc., Calgary, January 2011; and National Energy Board, Ottawa), about 441 000 km of pipelines, and 1.7 million km of seismic lines (Seismic Data Listing Service Inc., Calgary, Alberta, February 2011). Oil sand mining occurs near Fort McMurray, Alberta, in the central portion of the western sedimentary basin. Intensive development of this resource began about 2000 following pilot operations that began in 1967. Oil sands underlie about 14.2 million ha in north and eastern Alberta and about 27 000 ha in Saskatchewan. The surface mining area is limited to about 480 000 ha near Fort McMurray, of which 76 100 ha has been cleared or disturbed by oil sands mining (Government of Alberta, October 2012).

Dams or impoundments have been constructed on many of the major Canadian boreal rivers, primarily for hydroelectricity production (Fig. 9). As of 2011, there were 713 large dams (>5 m in height) in the boreal zone, most of which were built between 1920 and 1990 (Fig. 10), and there were another 290 dams between 3 and 5 m in height (J. Brandt, unpublished data). There are another 466 dams in the boreal zone for which height data are unavailable. Dams flood the land and alter both annual total and seasonal flow patterns. Most of the flooded areas were probably forested before the dams were constructed. In addition to the dams themselves, other infrastructure includes permanent, all-weather roads for access and utility corridors required to bring electricity to markets in more southern, urbanized areas of North America.

Despite these many developments, Canada's boreal zone remains sparsely populated. According to the 2010 census estimates, the population of the boreal zone was 3.7 million (derived by matching census division population estimates for 2010 (Statistics Canada 2011) to the spatial delineation of the boreal zone (Brandt 2009)), with an average density of 0.77 people/km² of land (global average density in 2000 was 45 people/km², Cohen 2003). Most people, however, live in small to medium-sized communities. Total employment in the region was 1.66 million in 2001, and about 60 000 individuals living in the boreal zone were directly employed by the region's forestry sector (Bogdanski 2008; Patriquin et al. 2009). Of the hundreds of communities in the zone, most depend on a single natural renewable or nonrenewable resource for their economic base.

In terms of global climate change, temperatures have been increasing with an increase of 0.7 °C in the last 150 years. However, mean annual temperatures were relatively steady during the period from the 1940s to the 1960s (Fig. 11). As shown in Fig. 12, the greatest annual warming has occurred in northwestern Canada, with temperature increases of more than 1.5 °C, whereas much of eastern Canada had warming of only 0.5 °C during the 1970–2004 period. Precipitation increased in most areas during the past century (Fig. 13). These increases amounted to 40% or more in eastern and northern areas, but a few areas in inland, continental regions witnessed decreasing precipitation.

[3]Mine is defined here as a mineral site where excavation and extraction of a deposit has occurred, not just exploration of the deposit.

Fig. 6. Active mines (blue circles) and smelters (yellow smokestacks) within Canada's boreal zone (adapted from NRCan 2009).

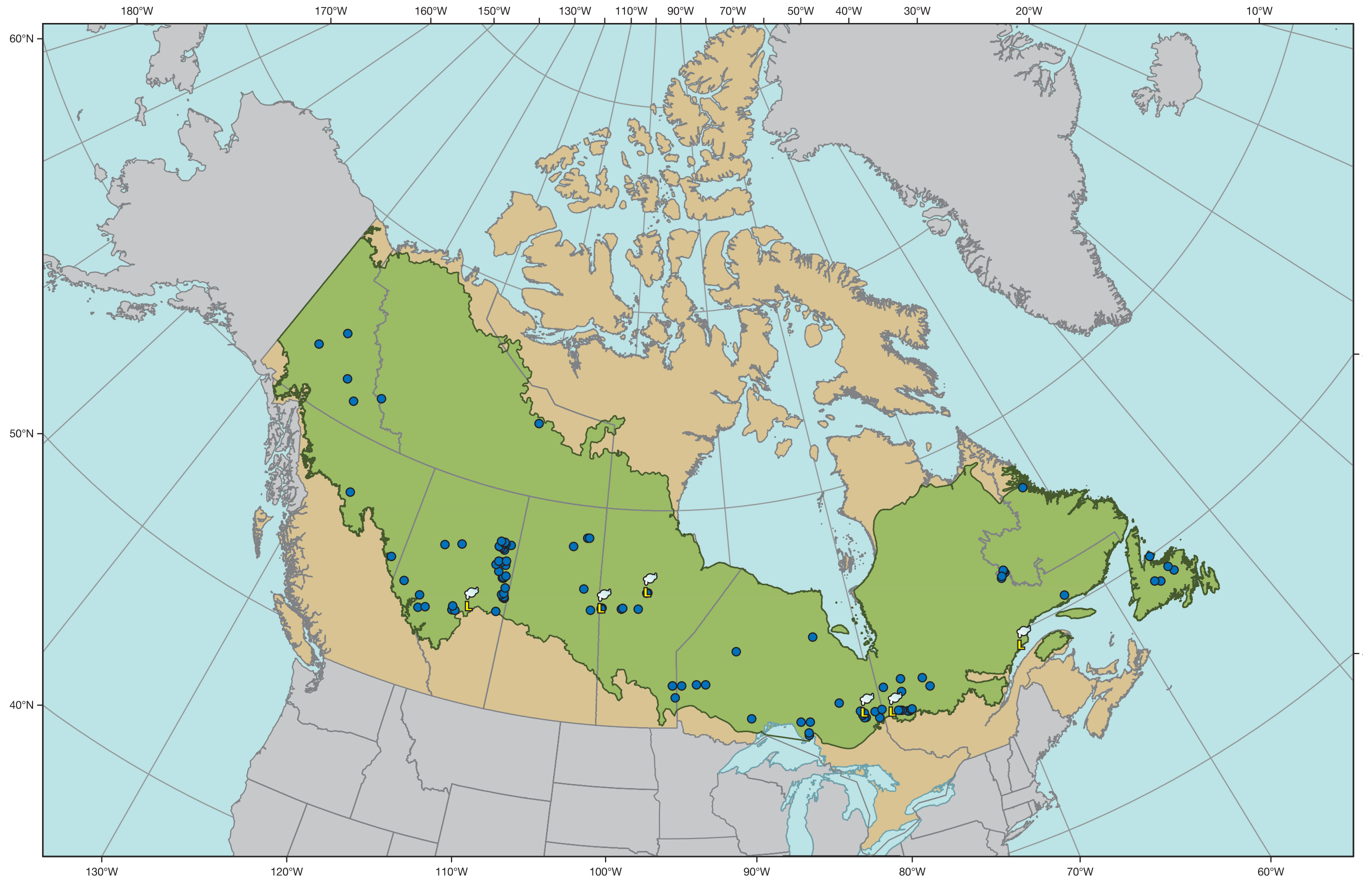


Fig. 7. Number of mines established in Canada's boreal zone by decade from 1850 to the present.

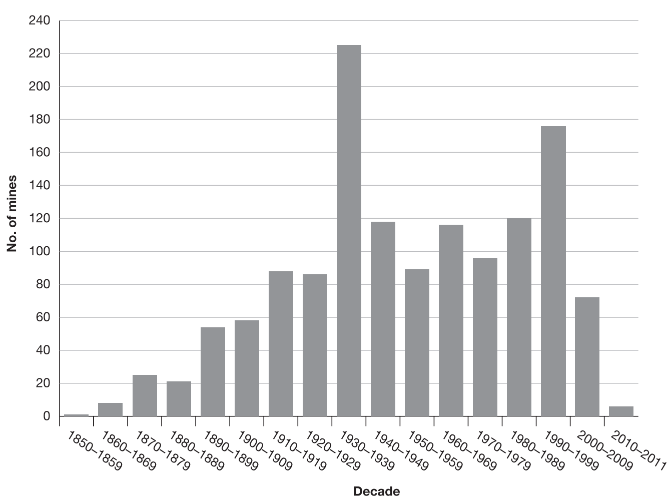
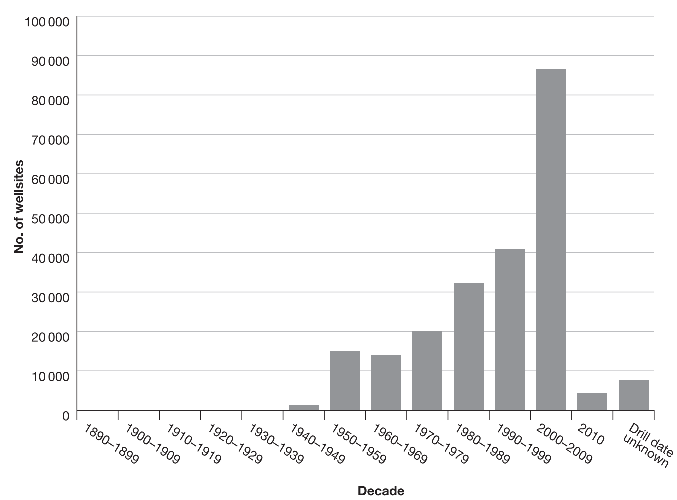


Fig. 8. Number of well sites drilled by the oil and gas sector in Canada's boreal zone by decade between 1890 and 2011.



3. Ecosystem health, sustainability, and environmental issues

The subjective term "ecosystem health" (or, more narrowly, "forest health") may be a source of confusion for scientists, forest managers, environmentalists, and the public alike, as differences exist within and among these various groups as to how the term is applied (Campbell and Liegel 1996; O'Laughlin 1996; Ferretti 1997; Kimmins 1997*a*, 1997*b*). An ecosystem consists of a complex of living organisms within an environment, with all components interacting and functioning together. Although individual humans, plants, and animals that are unhealthy may eventually die as a result of their disease, ecosystems (and human populations) will persist even if functioning is suboptimal, so long as the processes for regeneration are not impaired (Leopold 1949; Manion and Lachance 1992; Kimmins 1997*a*). There is no single, universally accepted definition of ecosystem health, but features commonly understood as contributing to the concept include maintenance of desirable functions and processes (e.g., ecological integrity and generation of goods and services), diversity of species, maintenance of productivity, resistance to biotic and abiotic

Fig. 9. Dams (blue circles) more than 3 m in height within Canada's boreal zone.

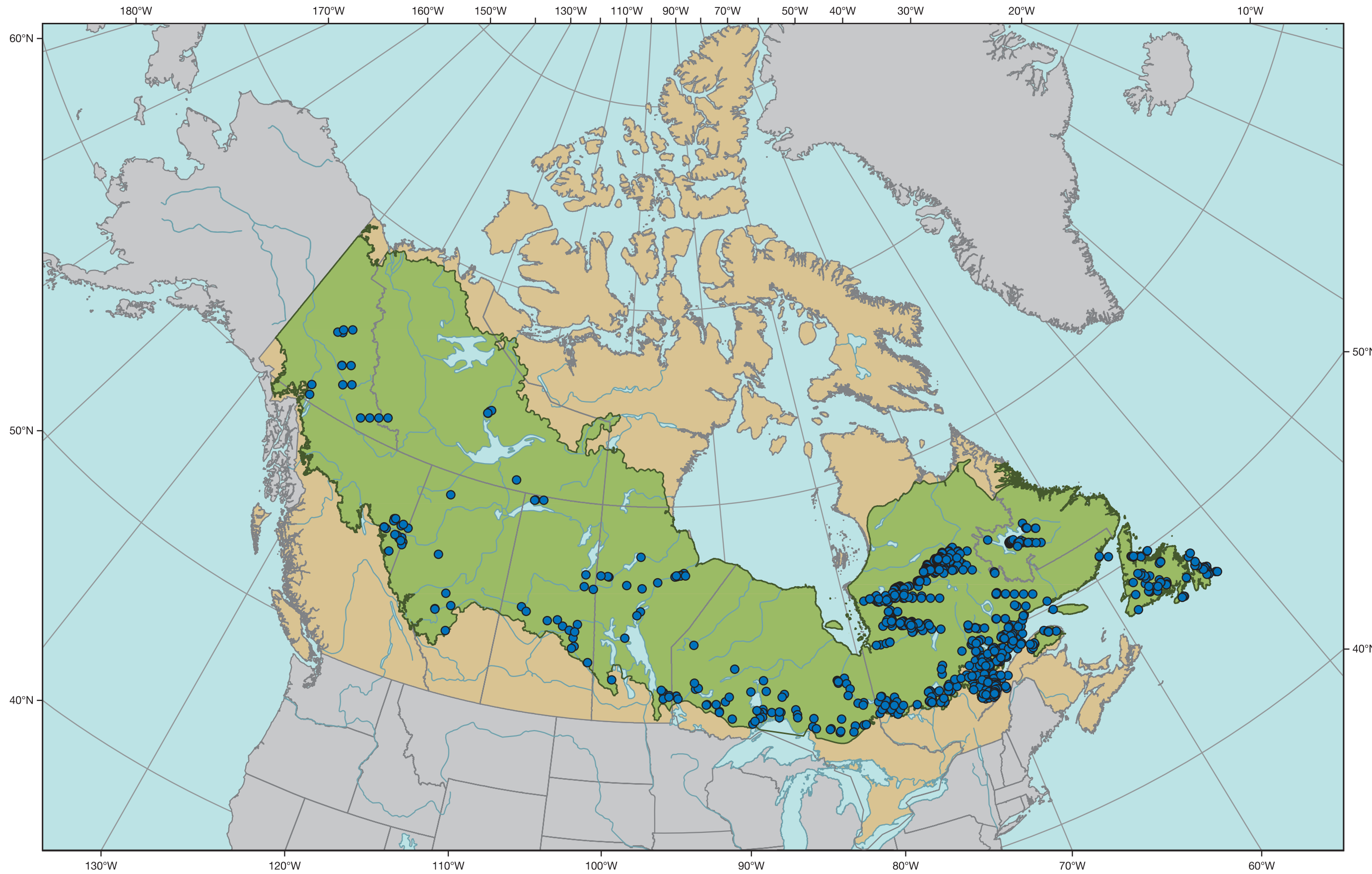


Fig. 10. Number of dams (>5 m in height) constructed in Canada's boreal zone by decade between 1900 and 2009.

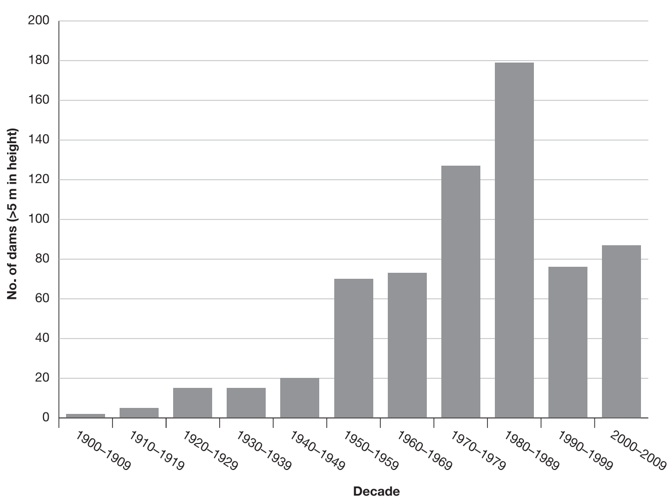
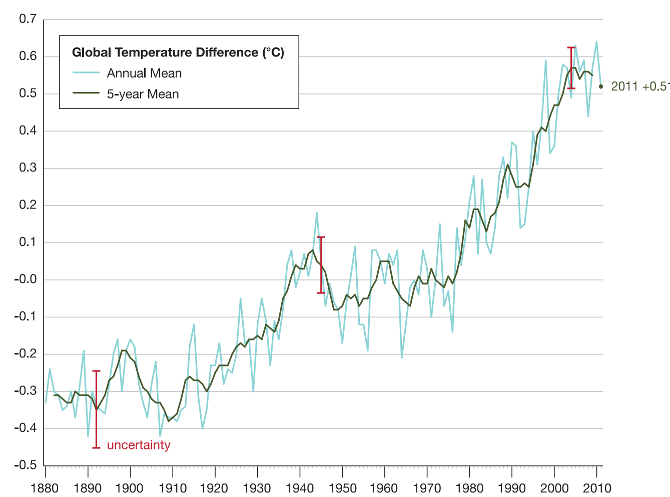


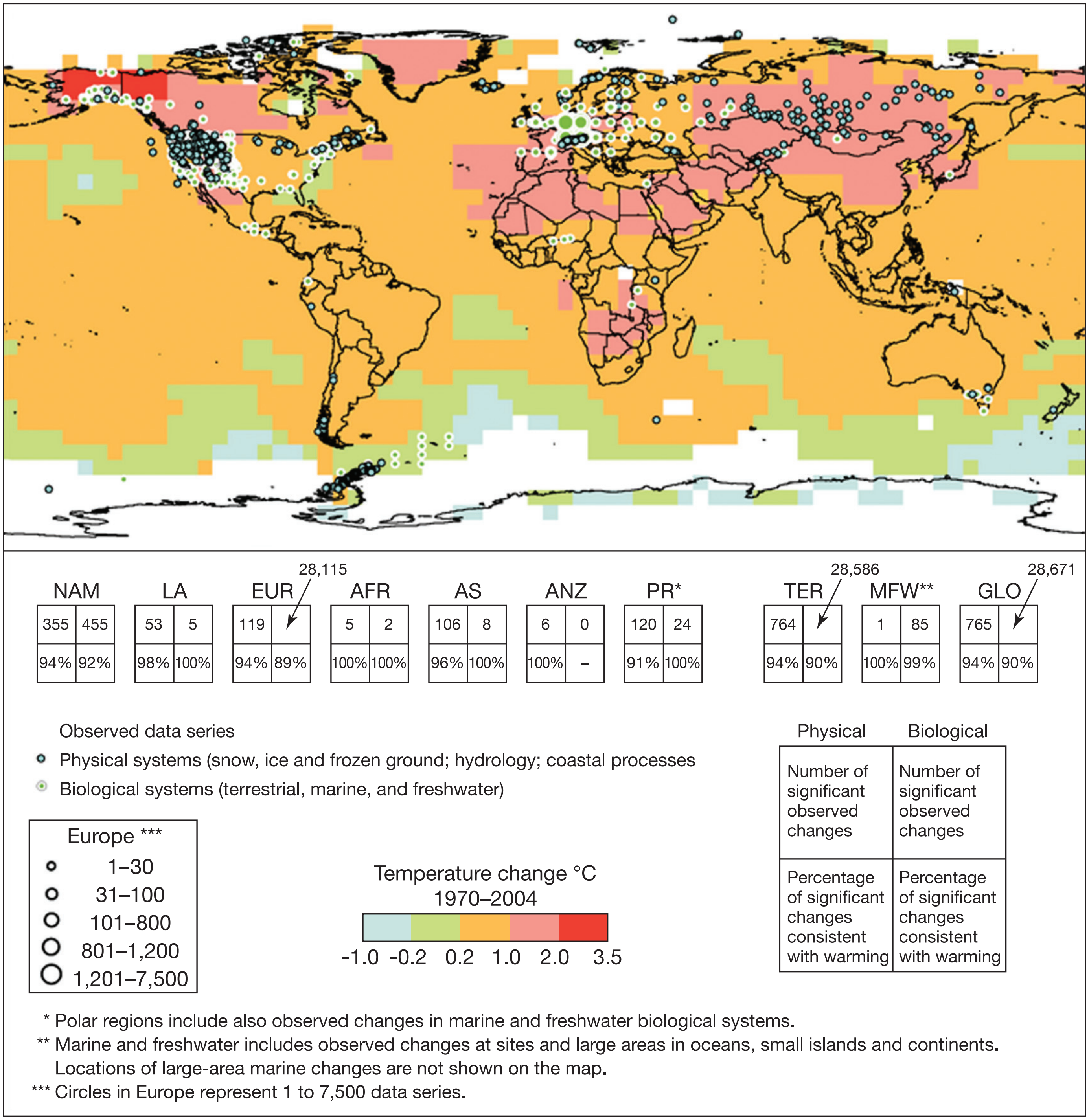
Fig. 11. Global mean temperature difference since 1880. (Source: NASA 2012).



stresses, and capacity for rejuvenation or renewal (CFS 1999; McLaughlin and Percy 1999; Allen 2001). In other words, ecosystem health refers to normal functioning of the entire system without anthropogenic or natural impediments.

Like forest health, sustainable development and sustainability have engendered much debate among environmentalists, resource managers, ecologists, economists, policy makers, and the public, particularly in relation to the meaning of the terms and the intent of the concepts when adopted into practice (Goodland and Daly 1996; Pezzoli 1997; Frazier 1997; Adamowicz and Burton 2003). For more than two decades, resource management policies in Canada have incorporated the concept of sustainable development, most influentially articulated in a document entitled "Our Common Future" (WCED 1987) and enshrined in the Convention on Biological Diversity (UN 1992). The World Commission on Environment and Development defined sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED 1987). The Commission also stated that the ability of the environment to meet present and future needs was con-

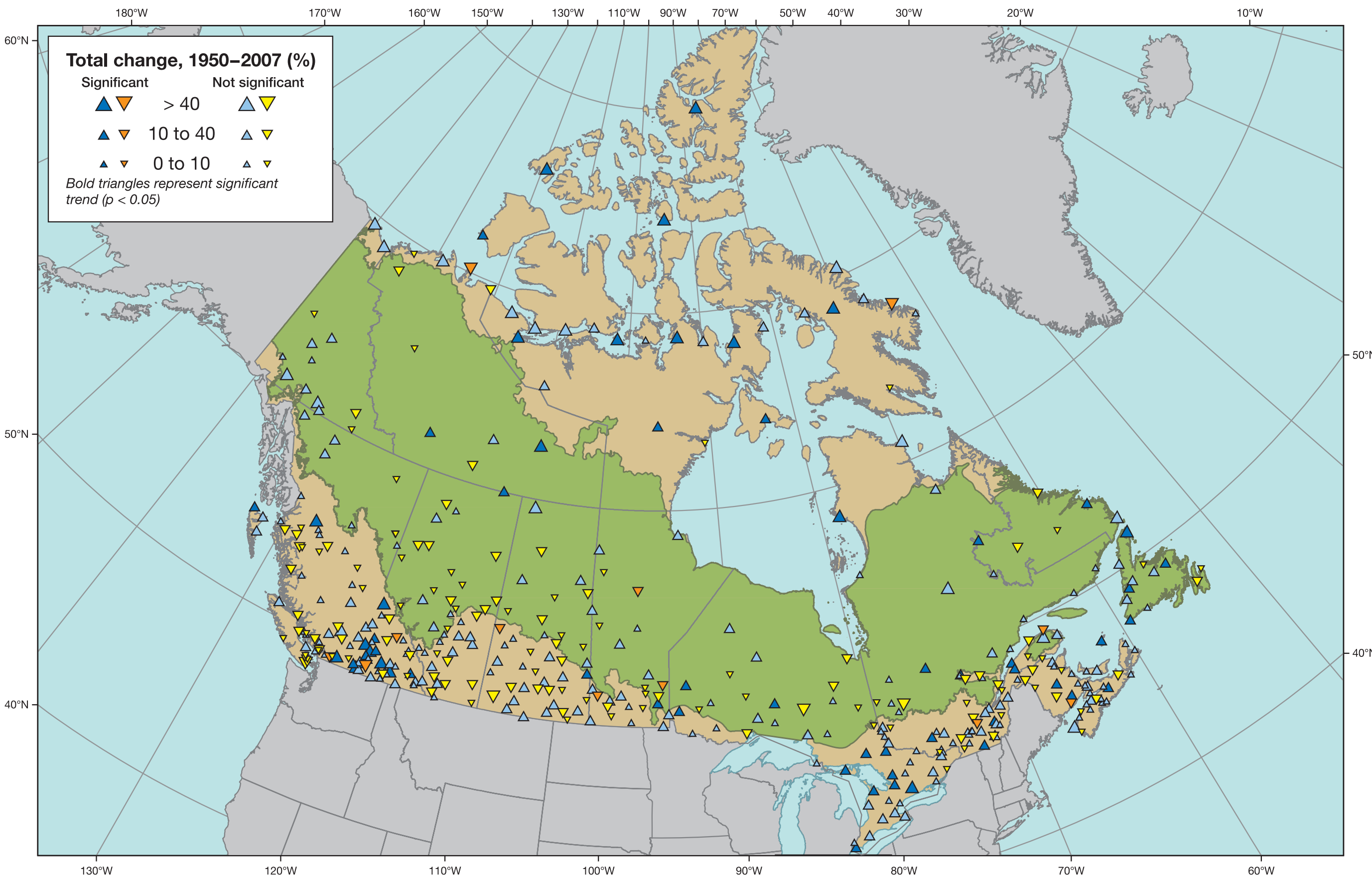
Fig. 12. Spatial distribution in annual temperature changes worldwide from 1970 to 2004. (Source: IPCC 2007*b*).



strained by the current state of technology and social systems. Sustainability describes an attribute of a system, one that enables the system to maintain its composition, structure, and function indefinitely. By extension and in the context of living systems, sustainability implies that the rate of extraction and consumption of natural resources, whether terrestrial or aquatic, cannot exceed the rate of resource renewal through time (Floyd 2002). Ecosystem sustainability, like ecosystem health, implies that the productivity, diversity, and overall integrity of ecosystems will be maintained in the long term. Economists and policy makers have tended to focus more on the concept of sustainable development (Pezzoli 1997; Weitzman 1997; Emmett 2006), while environmentalists and ecologists have focused more on the concept of sustainability (Floyd 2002; Raven 2002; McMichael et al. 2003). An unresolved issue in ecosystem sustainability is the spatial legacy of past resource management, the effects of which can persist for long periods on a landscape (Thompson and Welsh 1993; Drever et al. 2006; James et al. 2007). The concept of sustainable development replaced the ideas of sustained yield and multiple use (i.e., emphasizing resource production) that characterized former approaches to resource management.

Some wastes and pollutants from industrial and domestic activities can overwhelm the ability of natural ecosystems to process them (e.g., Lofts 2007). For example, many compounds that are

Fig. 13. Trends in annual precipitation in Canada. (Source: Environment Canada).



generated as wastes from industrial processes also occur naturally in the biosphere, where they are used by microorganisms as food (Atlas and Bartha 1987). To some extent, these wastes can be split into their constituent parts and can be cycled through both terrestrial and aquatic ecosystems by existing populations of microorganisms. However, in areas where extraction and consumption surpass renewal or where wastes accumulate, ecosystems will initially degrade, in terms of both complexity and productivity, and then will cease to exist and will be replaced by other flora and fauna that may be of lesser ecological, economical, or social value. We propose that such ecosystems, where an integrity or resiliency threshold or tipping point has been crossed, should be considered inherently unhealthy.

In contrast, there is evidence that where levels of biodiversity have been maintained and the soil protected, resilient ecosystems can, through time, revert to their pre-disturbance states when disturbances are halted for a sufficient period of time (Gunderson 2000; Drever et al. 2006; Thompson et al. 2009). In the interim, however, the ecosystems will not supply their full range of services. Valuation of ecosystem services (i.e., natural capital) may provide opportunities to link economic systems directly or indirectly to ecological integrity, and such solutions are now emerging from cooperation between economists and ecologists (Aronson et al. 2009).

Each person's perception of sustainability and the drivers of ecological change is unique, guided or influenced by their culture (e.g., religion or politics), education, perception of the present condition, and experiences. Given the brevity of the human lifespan and the rate of changes that have occurred to global systems, the baseline conditions perceived by each new generation differs, resulting in a "shifting baseline syndrome" (Pauly 1995). Essentially, the syndrome arises because the members of each generation accept as a baseline their perception of the services that ecosystems were providing at the beginning of their memories rather than some historical baseline; they then use this baseline to evaluate changes to the environment that occur during their lifetime and the need for conservation (Pauly 1995). In societies, people effect change through their political, judicial, social, economic, and academic institutions. However, the necessity for and rate of these changes are driven by the perceptions of the individuals comprising the society, and individuals' perceptions are subject to the shifting baseline syndrome. Thompson (2004) provides many examples of differential generational perception related to forests and wetlands in Canada.

Concerns about ecosystem health and sustainability are not new (e.g., Leopold 1949; Meadows et al. 1972), although the focus of these issues has evolved through time (Allen 2001). Until the late 1960s, the primary issues in forestry were losses of timber to fire, insects, and diseases. For example, during the 1960s and 1970s, fire was recognized as an important natural disturbance agent critical to the renewal of many North American forest types, and some suggested that the total exclusion of fire in forest ecosystems through suppression programs was undesirable (Leopold et al. 1963; Stocks and Simard 1993). Nevertheless, the philosophy of sustained timber yield prevailed, and decades of fire suppression followed, in attempts to maintain standing timber for harvesting. However, in 1988, fires in Yellowstone National Park and surrounding areas focused public and scientific attention in North America on fire suppression and management policies and rekindled debate about the role of fire as a natural disturbance agent (Christensen et al. 1989; Schullery 1989; Turner et al. 2003). Currently, fire management agencies are moving to strategies to allow wildland fire, where possible, to return to the landscape through managing rather than suppressing fire. Coinciding with

Table 4. Global environmental issues (listed alphabetically).

Issue	Description	Examples of key contemporary references
Biodiversity loss	Loss of species (i.e., extinction) or reduction in species' range, ecosystem simplification, ecosystem change, genetic loss, and reduced resilience	Sala et al. (2000); Mace et al. (2005); Rockström et al. (2009*a*, 2009*b*)
Climate change	Long-term regional climate changes occurring more quickly than species can adapt, resulting in a reduction in productivity, increased susceptibility to stress and pests, loss of species (i.e., ecosystem simplification), and habitat fragmentation	Hansen et al. (2008); IPCC (2007*b*)
Deforestation	Permanent or long-term land-use change, whereby the forest cover is removed, resulting in the loss of services provided by forests	Fitzsimmons (2002); Williams (2003, 2008)
Fragmentation	Parceling of the landscape into smaller pieces by the installation of roads, seismic lines, pipelines, railroads, power corridors, agriculture, other human disturbances including urbanization	Haila (2002); Wade et al. (2003); Manning et al. (2004); Fleishman and MacNally (2007)
Impaired biogeochemical cycling	Disruption of biogeochemical processes by point source emissions and long-range transport of various air and water pollutants related to combustion of fossil fuels, smeltering and processing of minerals, petrochemical processing, burning of forest, or flooding	Carou et al. (2008); Gruber and Galloway (2008); Flueck (2009); EPA (2010); Finzi et al. (2011)
Invasive alien species	Elimination or displacement of native species by non-native species introduced deliberately or accidentally, which can cause ecosystem change or species loss	Mack et al. (2000); Claudi et al. (2002)
Overharvesting	Situation in which the rate of removal of renewable resources exceeds the rate of regeneration	Post et al. (2002); Coulombe Commission (2004)
Resource management practices	Certain practices of various industrial sectors (e.g., open-pit mining, oil and gas exploration and extraction, logging, flooding from river impoundments) may overwhelm the resilience of ecosystems to recover from disturbances or other negative effects listed above	Kimmins (1997*a*); Rosenberg et al. (1995); Johnson (2003); Johnson and Halberg (2005)

the expansion of the environmental movement in the late 1960s and early 1970s, there was a worldwide shift toward understanding, assessing, and mitigating the negative environmental impacts of human development. During the 1970s, the first serious debates were initiated on various topics that remain of concern today, including deforestation of tropical forests as a result of slash-and-burn agriculture (Gómez-Pompa et al. 1972; Richards 1973; Sommer 1976); increased concentrations of carbon dioxide, primarily caused by combustion of fossil fuels (Bolin 1970; Broecker 1975; Woodwell et al. 1978); and the effects of acid rain and air and water pollutants on European and North American terrestrial and aquatic ecosystems (Cogbill and Likens 1974; Likens and Bormann 1974; Hutchinson and Havas 1980). Since then, there has also been a growing realization of the need to understand the cumulative and synergistic effects, in both space and time, of human development on ecosystems (CEARC and US NRC 1985; Cairns 1990; Schindler 1998; Schneider 2002).

Environmental issues of current concern for Canada's boreal zone and other areas of the world have been identified and described by scientists, concerned citizens, and nongovernmental organizations (Table 4). When considering these issues in the context of the environment (ecological goods and services), the economy (human-generated goods and services), and the needs of society, governments must balance the requirements of these juxtaposed elements, a laudable but difficult goal (see Kimmins 1997*a*). Where applicable in the Canadian context, governments at different levels address these environmental issues through various programs or through a multitude of economic or legislative instruments. At one extreme, all negative activities could be stopped through legislation, which would prevent any further permanent loss or damage. A less draconian approach would be for governments to introduce economic incentives to reduce negative impacts or reduce society's needs (or desires) for boreal resources (e.g., food, fiber, minerals, and energy). Perhaps these measures would best be directed at society's "wants", that is, those goods and services that are desirable but not essential for the betterment of society. Thus, if society's wants, or the number of individuals with those wants, are reduced, the demand for resources will be similarly reduced. Increasingly, however, societies can no longer be considered merely at the national scale. For example, Canada's boreal resources are used by citizens of many countries, so demand cannot be controlled by national policies and legislation. Human population size must also be considered at the global scale. Although these ideas are philosophical in nature, they form the crux of debates about sustainability and conservation of the ecosystems providing the services that we need and want (McMichael et al. 2003).

Rockström et al. (2009*a*, 2009*b*) recently conceptualized a novel approach to assessing the risks of various environmental issues. They identified and quantified planetary boundaries that they argued must not be crossed, because such transgression could cause abrupt, unacceptable environmental change, possibly leading to an environmental state less conducive to human development. The nine planetary boundaries quantified or estimated by Rockström et al. (2009*a*, 2009*b*) are related to biodiversity loss, interference with the nitrogen and phosphorus cycles, stratospheric ozone depletion, ocean acidification, global fresh water use, change in land use, chemical pollution, atmospheric aerosol loading, and climate change. Of these nine boundaries, only ocean acidification has no direct bearing on the circumboreal zone, although activities in the zone may have indirect effects on ocean acidification. Running (2012) recently suggested another boundary, net primary production, which he considers measurable and integrative of many of the other boundaries of Rockström et al. (2009*a*, 2009*b*).

4. Boreal review papers

Among Earth's terrestrial biomes, the circumboreal zone is unique because it has limited human occupation, extensive undeveloped areas, many intact predator–prey processes, a huge storehouse of carbon, and few invasive species. However, numerous types of developments across Canada may be affecting its boreal ecosystems cumulatively, and in a manner unknown in the previous century, including forest management, mining, hydroelectric development, and oil and gas exploration and development.

Forest and resource management policies in Canada's boreal zone have evolved during the past 60 years, from primacy of resource extraction, through multiple and then sustainable use, and finally to the emulation of natural disturbances in the case of forestry. These changing policies make it difficult to determine the long-term effects of specific resource management practices on ecosystems and animal communities, because the effects may be changing in response to changes in specific management methods and policies. Furthermore, our knowledge of responses to change is incomplete, as no mechanically harvested forest or reclaimed site has yet attained mature or old-growth age in boreal forests (Thompson and Welsh 1993; Drapeau et al. 2000).

The review papers that follow in this series are intended to synthesize available scientific evidence of the impacts of human development, resource use, and climate change on terrestrial and aquatic ecosystems in the boreal zone of Canada. The following four overarching questions framed the scope of these reviews:

1. What are the effects of resource management on boreal ecosystems?
2. How do we know if the boreal zone and its ecosystems are healthy?
3. To maintain a healthy boreal zone, how much of the zone do we need to protect?
4. How can management practices in the boreal zone be adapted to climate change, and how can they help to mitigate it?

Nested within these broad questions are an entire suite of more specific questions, which are addressed by individual papers, with some overlap as appropriate.

As noted above, the concepts of ecosystem health and sustainability include maintenance of desirable ecosystem functions and processes (e.g., ecological integrity and generation of services), diversity of species, maintenance of productivity, resilience to biotic and abiotic stresses, and capacity for rejuvenation or renewal. Boreal ecosystems originated from previously glaciated landscapes and remain prone to and driven by disturbances. Thus, they have evolved and adapted to severe and episodic disturbances. Ultimately, the question becomes whether the adaptive capacity of boreal ecosystems, and hence their resistance and resilience to cumulative natural and anthropogenic disturbance, have been impaired through extinctions, habitat loss, fragmentation, or change or loss of ecosystem processes. An examination of these issues is important because resource industries operating in Canada's boreal zone are increasingly being judged domestically and internationally based on their environmental reputation, which affects their access to markets for renewable forest products, minerals and metals, and energy products, and the hundreds of communities and many First Nations where theses products are extracted and refined. Consequently, Lavigne et al. (Manuscript in preparation) review the dynamics of boreal forests and the sustainability implications of disturbance and recovery. These authors consider factors affecting current sustainability of boreal forests, limiting their consideration of forest values to primary production and the production of commercial timber. Maynard et al. (In Press) consider soil nutrient cycling in boreal forests. These nutrient cycles provide adequate and balanced supplies of the elements (e.g., nitrogen, phosphorus, and potassium) necessary for life, which are foundational for all other ecological services (Hassan et al. 2005). Natural disturbances and human activities may have long-lasting effects on these biogeochemical processes (Richter and Mobley 2009). Venier et al. (Manuscript in preparation) and Kreutzweiser et al. (2013) review the effects of resource management on the biodiversity of terrestrial and aquatic boreal ecosystems, respectively. Biodiversity underpins and supports many ecosystem services used by humans (Diaz et al. 2005), while enabling ecosystems to respond to environmental change and maintain their resilience (Thompson et al. 2009). Langor et al. (Manuscript in preparation) assess the status and impacts of non-native species in Canada's boreal zone. Non-native species threaten the productivity and native biodiversity of boreal ecosystems. Webster et al. (Manuscript in preparation) review the status and prognosis of water and wetlands in the boreal zone. Water, along with forests, is a characteristic feature of Canada's boreal zone, and the terrestrial and aquatic ecosystems are intricately linked. About 13% of the area of the boreal zone is covered by open water (lakes, ponds, river, and streams), and more is covered by wetlands. The quantity and quality of fresh water will likely become two critical issues in the 21st century as the climate changes and the demands of a rapidly growing global population continue to increase (Shiklomanov and Rodda 2003; Rockström et al. 2009*b*). Andrew et al. (In press) examine the issue of protected areas in Canada's boreal zone. Protected areas are considered an important component of a land-use strategy for maintaining habitat, reservoirs of biodiversity, intact ecological processes, and baselines against which changes in unprotected areas can be measured. An unresolved issue is the required extent of protected areas in the present boreal zone and the boreal zone of the future (with climate change).

Together, this first group of papers reviews the state of science with respect to boreal ecosystems as they currently exist and the impacts of resource development. However, climate change is an unresolved factor that will affect the future state of these ecosystems. Therefore, a second group of papers deals with questions related to climate change. Kurz et al. (2013) consider the present and future role of the Canadian boreal zone in the carbon cycle. Boreal ecosystems store and cycle vast amounts of carbon. Although currently considered a sink for carbon, Canada's boreal forests may become a carbon source in the near future with further warming. Forest management, wood products, land use, and disturbances are all important considerations for carbon sources and sinks. Price et al. (2013) review the impacts of climate change on forested boreal ecosystems. They consider the possible and likely effects of climate change on the structure and function of these ecosystems; the implications for supplies of goods, services, and ecological benefits; and potential feedback effects resulting from climate change. Gauthier et al. (In press) examine resource management and climate change adaptation. They review the consequences of climate change for sustainable forest management in boreal forests and consider how adaptation measures might be incorporated in planning processes at the strategic, tactical, and operational scales. Lemprière et al. (2013) review the mitigation potential of the Canadian boreal zone in terms of ecosystem carbon and greenhouse gas emissions, carbon in harvested wood products, and bioenergy. Although the global and national mitigation challenge is large, mitigation opportunities involving boreal ecosystems exist and need to be part of broader efforts at dealing with climate change.

Concerns about the effects of resource management and development on the health and sustainability of boreal ecosystems are central to the debate about environmental stewardship. Because 28% of the world's boreal zone lies within Canada and because forests, water, and ecosystem services are increasingly seen as a global resource, national and international attention on Canadian boreal ecosystems is focused on ensuring sustainability and reducing degradation of ecosystems where it has already occurred. Sustaining Canada's boreal ecosystems and the ecological services they provide for future generations requires detailed scientific knowledge and understanding of natural processes and drivers of change. It also requires knowledge and understanding of how to emulate these processes through resource management and how the integrity and resilience of these natural processes are affected by anthropogenic factors and climate change. Science is the foundation for ecologically based resource management and policy making by various stakeholders (Brundtland 1997). Our intent in this series is to review and synthesize the available science to aid those responsible for the management of boreal ecosystems and natural resource development. A secondary outcome of the work will be to identify key knowledge gaps that need to be filled in the near future to improve future assessments of Canada's boreal zone.

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