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ORIGINAL ARTICLE

Climate change and mining in Canada

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Abstract Climate is an important component of the operating environment for the Canadian mining sector. However, in recent years mines across Canada have been affected by significant climatic hazards, several which are regarded to be symptomatic of climate change. For the mining sector, climate change is a pressing environmental threat and a significant business risk. The extent to which the mining sector is able to mitigate its own impact and adapt to climate change will affect its long-term success and prosperity, and

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have profound economic consequences for host communities. This paper draws upon case studies conducted with mining operations in Canada involving in-depth interviews with mining professionals and analysis of secondary sources to characterize the vulnerability of the Canadian mining industry to climate change. Five key findings are discussed: i) mines in the case studies are affected by climate events that are indicative of climate change, with examples of negative impacts over the past decade; ii) most mine infrastructure has been designed assuming that the climate is not changing; iii) most industry stakeholders interviewed view climate change as a minor concern; iv) limited adaption planning for future climate change is underway; v) significant vulnerabilities exist in the post-operational phase of mines. This paper argues for greater collaboration among mining companies, regulators, scientists and other industry stakeholders to develop practical adaptation strategies that can be integrated into existing and new mine operations, including in the post-operational phase.

Keywords Adaptation · Canada · Climate change · Hazards · Industry · Mining · Planning · Resource management · Vulnerability

1 Introduction

The link between climate change and human activities is well established (IPCC 2007a, b). Increases in temperature, changes to the frequency and magnitude of extreme weather events, changes in precipitation and altered seasonal patterns have been documented across Canada and elsewhere, and these changes are projected to continue in the future with implications for ecosystems, industrial activity and society (e.g. Lemmen et al. 2008; Paavola 2008; PIEVC 2008; Stringer et al. 2009; Pearce et al. 2010). It is now widely accepted that some level of adaptation is necessary to deal with current and expected future climatic change (e.g. Berry et al. 2006; Leary et al. 2008; Lobell et al. 2008; Tribbia and Moser 2008). Acknowledging this fact, research has broadened from focusing solely on the causes and nature of change to its human dimensions (Ford et al. 2010a). For individual industrial sectors, and regional and national economies, identifying and characterizing impacts and vulnerabilities is important because changing environmental conditions can have major implications for economic viability and socio-cultural well being. By identifying and anticipating vulnerabilities, stakeholders, practitioners and regulators can take pro-active approaches to moderate risk. Our understanding of the implications of climate change for major industrial activities in Canada, however, remains limited, with climate change research and action typically focusing on mitigation (Lemmen et al. 2008; Seguin 2008).

Primary economic activities, which are the mainstay of local economies in many parts of Canada, are particularly sensitive to the consequences of climate change because of their immediate dependency on the natural environment (Ogden and Innes 2007; Parkins and MacKendrick 2007; Lemmen et al. 2008; Ford et al. (2010c, in press). The potential vulnerability of many of these economic activities (e.g. forestry, fishing, mining) has considerable regional significance because they are often the dominant economic activity for large regions and are basic to the tertiary activities that occur locally and elsewhere.

Such regionalization is typified by the Canadian mining industry, which, tied to the nation's diverse geology is based in hundreds of widely dispersed, often rural locations. The sector is economically important employing approximately 360,000 people in mineral extraction and in the value-added smelting, fabrication and manufacturing areas and contributes approximately $42 billion a year to Canada's Gross Domestic Product (GDP) ($10 billion in mineral extraction and $32 billion in mineral processing and manufacturing) (MAC 2008). As of January 2008, there were approximately 766 mining establishments in more than 115 communities across Canada (concentrated in Ontario and Quebec), including 63 metal mines and 703 non-metal mines (Fig. 1). Despite the importance of mining and the susceptibility to climate change, few, if any, studies have directly examined the implications of climate change for mining operations (Ford and Pearce 2007; Ford et al. 2008). Where potential impacts have been noted it has most often been indirectly as part of broader climate change reports (e.g. Instanes et al. 2005; Lemmen et al. 2008). This work has identified some key climate vulnerabilities in the mining sector.

Firstly, transportation routes and mining infrastructure are susceptible to structural weakening and failure due to increased frequency and severity of extreme weather events and climate variability (Auld and MacIver 2006; Infrastructure Canada 2006; Robertson 2006; Scales 2006). Depending on the nature and location of a mine, containment facilities, buildings, energy sources, and mine site drainage may be affected by permafrost thaw, rising average temperatures, stronger winds, changing water levels and ice composition, and greater intensity and frequency of precipitation. In northern regions, these changes could be particularly problematic, weakening structural integrity and safety of ice roads, bridges, pipelines and airstrips (Instanes et al. 2005). Furthermore, the walls of open-pit mines and contaminant structures may not safely withstand melting/exposed permafrost (Instanes et al. 2005; Furgal and Prowse 2008; Prno 2008). Climate change, however, may

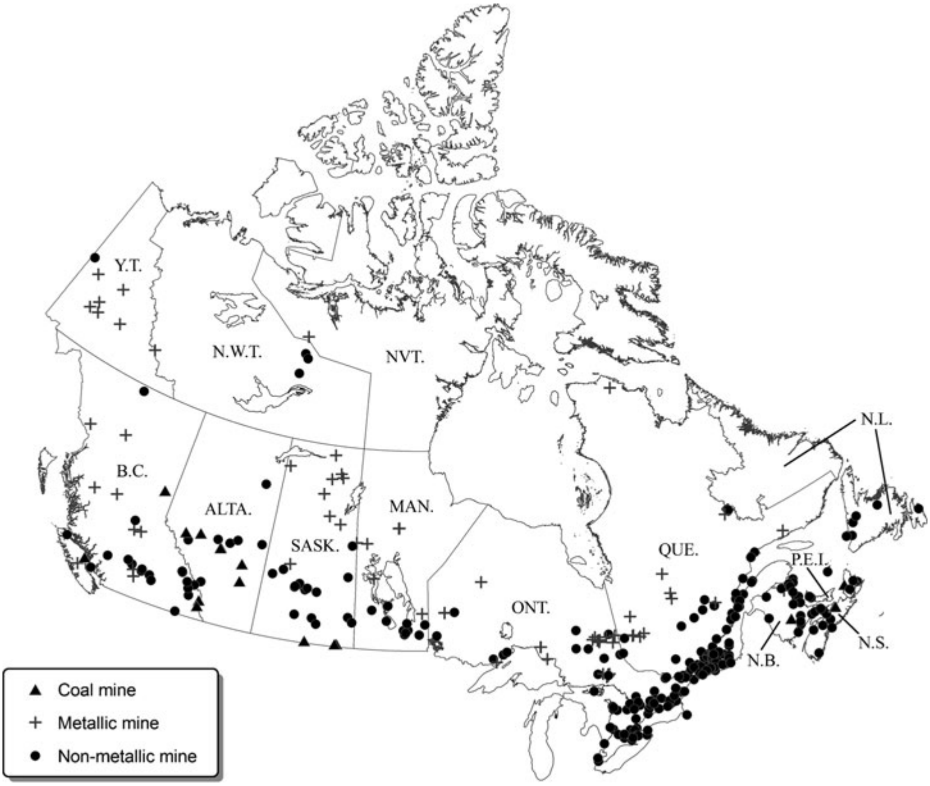

Fig. 1 Location of coal, metal and non-metal mines in Canada

also have benefits: melting arctic sea ice, for example, is expected to lead to longer shipping seasons, shorter transportation routes, and greater exploration opportunities (Instanes et al. 2005; Comiso et al. 2008; Lemmen et al. 2008). Secondly, climate change is expected to affect mineral processing operations (UNEP-FI and SIWI 2005; Brown et al. 2006; Lemmen et al. 2008). Given that some mine processes are highly water dependent (e.g. sodium sulphate mining), increased water scarcity could impact production rates, dust suppression efforts, mine drainage, and the covering of tailings (Kyhn and Elberling 2001; Bjelkevik 2005; IPCC 2007a).

Developing adaptation strategies to plan for and cope with current and expected future climatic changes has been suggested to ensure the economic viability of mining operations and to safeguard the environment in which mines operate. With regards to infrastructure, Auld et al (2006) suggest employing “no regrets” measures (actions with net social benefits) while encouraging continued learning about adaptation opportunities and capacity. Other scientists and regulators have also called on mining operations to develop long-term adaptation strategies (Mills and Andrey 2002; ACIA 2005; Government of Canada 2006; Infrastructure Canada 2006; Lemmen et al. 2008). Elsewhere, research on industry perceptions of climate change (Ford et al. 2010b, c in Press), indicates that climate change is an emerging concern for the mining industry but limited action has been taken to plan for or adapt to changing conditions.

The Mining Association of Canada (MAC) recognizes climate change as a serious concern for mining, but has for the most part focused efforts on mitigation rather than adaptation (MAC 2004; MAC 2009). Reducing greenhouse gas (GHG) emissions and increasing energy efficiency has been the most common approach taken by mining operations in Canada for addressing climate change. This focus is reflected in trade journal publications, which have discussed topics including: emissions caps and carbon-emissions related legislation (Ednie 2002; The Northern Miner 2007), company specific emission reduction initiatives (The Northern Miner 2000), policies to reduce GHGs based on the Kyoto Protocol (Ion 2004), carbon emission trading schemes and offsetting (Ednie 2002; Wise 2005), emission mitigation technology (Ednie 2002), and carbon sequestration (Ednie 2002; Ion 2004; Canadian Mining Journal 2005; Coal Age 2007).

Mining operations are also sensitive to ‘the politics of climate change’ including the public perception of a company’s commitment to addressing climate change and the development of government regulations to govern GHG emissions. For example, the onset of ‘cap and trade’ systems and/or carbon taxes could alter how some mining companies make financial and operational decisions. Those companies caught unprepared for new legislation may face significant economic and regulatory repercussions. Of particular concern for some mining sector representatives is climate change legislation that is designed without significant industry input, and that leads to hefty economic repercussions for the sector. Large-scale operations including smelter facilities in Northeastern Ontario could be at particular risk because of their large emissions and highly visible public profiles.

This paper uses a vulnerability framework described by Ford and Smit (2004) and Smit and Wandel (2006) to document and describe how mining operations in Canada are exposed and sensitive to climate change, and assess adaptive capacity to manage current and expected future changes. The paper begins by describing the methodology used to assess vulnerability of the sector and introduces the five case studies. The results section first discusses current followed by future vulnerabilities linked to climate change, and concludes by identifying opportunities for advancing adaptation planning in the mining sector.

2 Methodology

2.1 Vulnerability approach

We use a vulnerability approach to identify and characterize the vulnerability of the Canadian mining sector to climate change (Ford and Smit 2004; Smit and Wandel 2006). The framework conceptualizes vulnerability as a function of exposure-sensitivity to climatic risks and the adaptive capacity to deal with those risks. *Exposure-sensitivity* refers to the propensity of mining operations to be affected when exposed to certain climatic conditions. It is a joint property of both the nature of the mining operation in question (e.g. location, mine type) and the characteristics of climatic conditions (e.g. magnitude, frequency, spatial dispersion, duration, speed of onset, and timing) (Smit and Wandel 2006). *Adaptive capacity* refers to the ability of individual mines and the sector as a whole to address, plan for, and/or adapt to these conditions. In this conceptualization, vulnerability is viewed as being determined by economic, political and climatic conditions and processes operating at multiple scales, which affect mining sector exposure-sensitivity and adaptive capacity. This is consistent with other conceptualizations of vulnerability in the climate change literature (Kasperson and Kasperson 2001; Turner et al. 2003; Duerden 2004; Schröter et al. 2005; Smit and Wandel 2006; Fussel 2007; Keskitalo 2008; Nelson et al. 2010).

A two stage analytical framework is used to empirically employ the conceptual model to assess vulnerability of the mining sector to climate change (Ford and Smit 2004). Analysis begins by identifying current climate vulnerabilities faced by the sector, which directly feeds into an assessment of vulnerability to future climate change. Potential adaptation responses are considered in all stages of the framework. The four steps of the analytical framework for assessing vulnerability in the mining sector are:

- identifying the climate-related conditions or risks that are relevant to mining operations and how operations are affected (referred to as exposure-sensitivities); and
- identifying and assessing the strategies and management practices employed to cope with and adapt to exposure-sensitivities.

Together, these components are considered ‘current vulnerability.’ The next two steps relate to ‘future vulnerability:’

- estimating future exposure-sensitivities based on likely changes in current exposure-sensitivities and the potential for new risks to emerge; and
- assessing the capacity of current strategies and management practices to cope with and adapt to projected future exposure-sensitivities.

2.2 Mining case studies

The vulnerability framework was applied in five in-depth case studies from mining regions across Canada to identify and characterize current and future vulnerability to climate change (Fig. 2). The case studies reflect the diversity of the Canadian mining sector, and include mines located in newly developed and well-established mining regions, in wilderness areas, and in the urban-rural interface; mines dependent on climate sensitive transportation networks (including ice roads), and mines well-serviced by transportation infrastructure; mines located in areas subject to Indigenous land claim agreements; and operations ranging from mining gemstones to aggregates to base metals. The regions include:

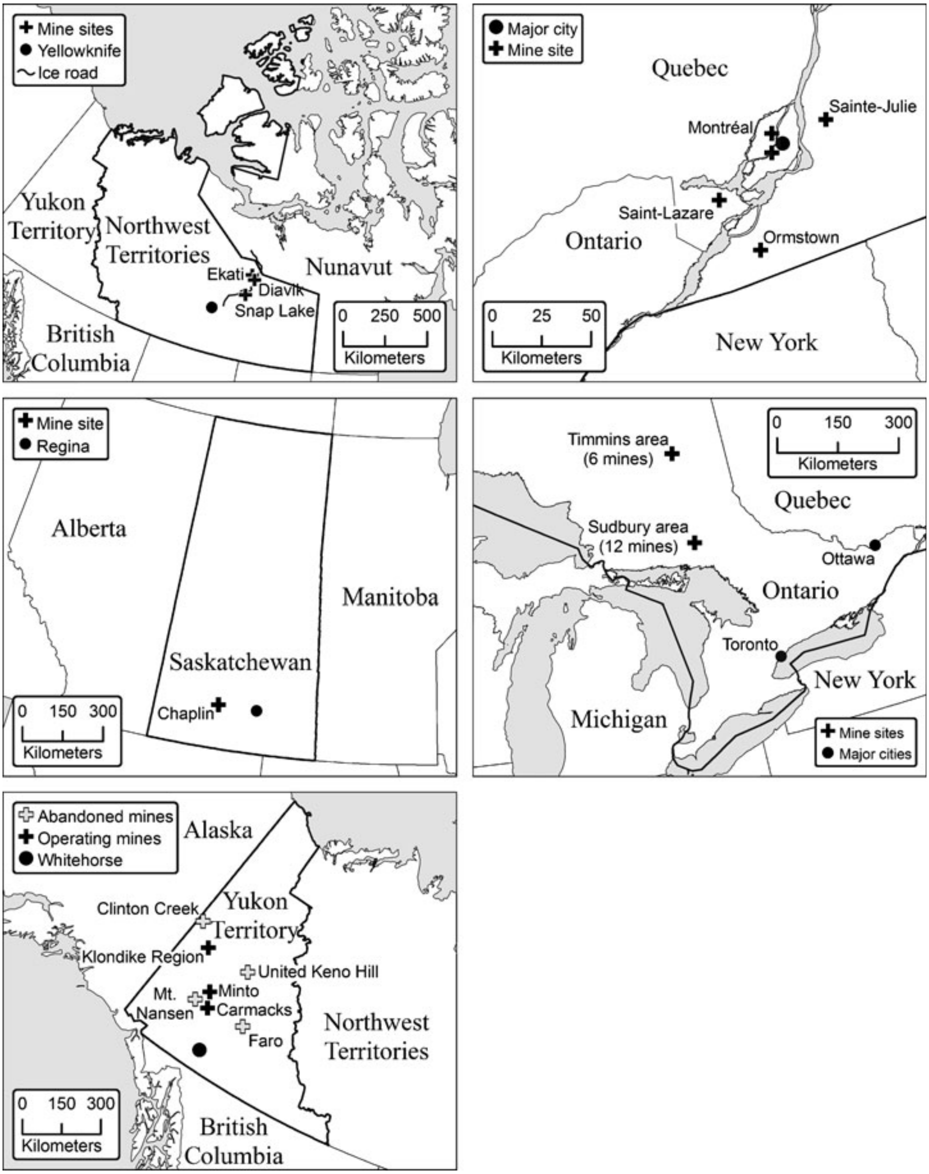

Fig. 2 Location of mining operation case studies in the respective province or territory in Canada

2.2.1 Diamond mining in the Northwest Territories

The diamond mining industry in the Northwest Territories (NWT) is the largest contributor to the NWT's GDP, representing more than 50%, and is estimated to be worth over $1.4 billion (NRCan 2008). Canada produces 11.5% of the world's diamonds on a value basis making it the world's third largest diamond producer by value (NRCan 2007a). There are three diamond mines operating in an area approximately 200-300 km northeast of the territorial capital, Yellowknife—BHP Billiton's *Ekati*, Diavik Diamond Mines Incorporated's *Diavik*, and De Beers Canada's *Snap Lake*. The 568 km long seasonal 'ice road' is the only ground transportation link between the diamond mines and cities in the south, and transport trucks bring the majority of fuel and supplies into the mines over the road during the winter.

2.2.2 Mining in the urban-rural interface in Southwestern Quebec

This case study focuses on mining operations in a populated setting: the Montreal area in southwestern Quebec. This provides insights into the nature of current and future climate change vulnerability of mine operations in areas that are well serviced by transportation and logistics infrastructure, and operating in locations with high population density and competing land uses. The mining operations studied include two sand quarries, two limestone quarries and one dolomite quarry all of which are within 100 km of Montreal. The companies selected for the interviews reflect a cross section of quarry operations in the province, including small family-run companies and large multinational firms.

2.2.3 Sodium sulphate mining in Saskatchewan

Saskatchewan is the fifth largest sodium sulphate (a.k.a. Glauber's salt or mirabilite) producing region in the world with a production capacity of approximately 530,000 tons annually, which accounts for 6% of total annual global production. All sodium sulphate reserves in the province are naturally occurring in alkaline lakes, meaning that extraction is sensitive to climate and dependent on water availability. The Saskatchewan Minerals, Inc. sodium sulphate mine in Chaplin is one of the oldest in the province and is located along the Trans-Canada Highway and the mainline of the Canadian Pacific Railway, providing easy access to transportation networks. The mine produces high quality sodium sulphate with a minimum quality standard of 99% purity, allowing the company to access the global powder detergent markets as opposed to the less active salt-cake markets.

2.2.4 Base metal and gold mining in Northeastern Ontario

Northeastern Ontario has long been one of the principal mining regions in Canada. Centered on the cities of Sudbury and Timmins, the region is known for its base metal (e.g. nickel, copper) and gold mining, and provision of specialized mining services. Some of the largest mining companies operating in Canada and globally are located here. Sudbury, with a population of approximately 160,000 people, is the heart of the region's mining industry. Known primarily for base metals, the Sudbury basin has four companies operating thirteen mines. Timmins, with an approximate population of 42,500 people, is better known for its gold production, and seven gold and base metal mines are currently operating in the area.

2.2.5 Mining in the Yukon Territory

The Yukon is one of the oldest mining regions in Canada. A century ago the Klondike Gold Rush in the central Yukon established the popular image of mining in the north as a rugged endeavour set in an unforgiving climate. Placer mining was the earliest activity, but hard-rock mining has become the most dominant. Subsequently the fortunes of the Yukon have been closely associated with the mining industry (Government of Yukon 2008). The industry in the Yukon has a long history of adapting to a complex interplay of market conditions and climate and its experiences are germane to understanding the relative vulnerability of mining to climate change. In essence, factors impacting the viability of mining in the Yukon typify mining environments throughout the north (high costs, long transportation distances, climatic extremes),

2.3 Methods

A consistent research approach was taken in each case study. Firstly, mine operations in the five regions were identified and interviewees were selected using a purposive sampling technique that included mine managers, engineers, operations coordinators and other knowledgeable people with respect to mine operations. A snowball sampling method was also used, whereby interviewees identified other knowledgeable people to interview. A total of 46 semi-structured interviews were conducted across the case studies in summer and fall 2008. The interviews had five objectives: i) document those climatic risks that mines have had to deal with and are currently dealing with; ii) identify how these risks are experienced and managed; iii) document factors that influence exposure-sensitivity to climatic risk and constrain/enhance adaptive capacity; iv) identify efforts being undertaken to reduce greenhouse gas emissions; and v) consider what climate change might mean for future operations. Interviews took place in-person at mine sites and by phone, and were in English except in Quebec where they were conducted in French. A fixed list of questions was avoided in favour of an interview guide that identified the key themes to cover (Table 1). This allowed for flexibility in the interview as participants were guided by the interviewer's questions, but the direction and scope of the discussion often explored other areas of interest. The interviews were complemented with analysis of secondary sources of information including academic journal articles, government reports, newspaper articles, books, company reports, and environmental impact assessments (EIAs). These sources

Table 1 Key themes in the interview guide and examples of some topics covered under each theme

Key theme	Example of topics covered
Respondent information	• Length of time in current job • Job description • Nature of mine operation working for
Operational challenges (current exposure-sensitivity and adaptive capacity)	• What are the main challenges facing the mining operation? • What climatic risks affect operations? • What management strategies exist for handling climatic and non-climatic risks?
Current climate change (current exposure-sensitivity and adaptive capacity)	• Have changes in climatic conditions been observed? • Are they affecting operations? • How is the mine managing these risks? • Is the company taking action on mitigation?
Future climate change (future exposure-sensitivity and adaptive capacity)	• If these changes were to continue in the future, how would they affect operations? • Is the company taking any measures to plan for potential future climatic changes? • What adaptations are possible? • Is action being planned to reduce GHGs?

were analyzed using the vulnerability framework to identify current and future exposure-sensitivities and adaptive capacities of various mining operations.

2.4 Research limitations

It is noteworthy that the characterization of climate change vulnerability differs in terms of breadth and depth for each case study. This occurred for a number of reasons. Firstly, willingness to be interviewed varied across the case studies, reflecting time availability of potential interviewees and their interest in the project. Secondly, for established mining regions (e.g. northeastern Ontario) and those regions that are more climate-sensitive (e.g. Northwest Territories, Yukon), the literature is more comprehensive as it pertains to climate vulnerability. For other regions the literature on climate change vulnerability is limited (e.g. southwestern Quebec). Thirdly, case studies range from focusing on individual mine sites (e.g. diamond mines in the NWT) to geographically constrained areas (e.g. south-western Quebec), to large regions with a diversity of mine operations (e.g. Saskatchewan, Yukon). Moreover, for newer mining operations (especially mines developed in the last decade) some information on climate vulnerability is contained in environmental impact assessments (EIAs). When sampling a cross section of an industry as diverse as the Canadian mining sector it is inevitable that there will be differences in the breadth and depth of analysis between the case studies. It is also noteworthy that in some case studies the researchers operated on the principle of anonymity to interviewees at mine sites (e.g. Quebec) reflecting personal preference and a recruiting technique, in the other case studies this was not necessary.

3 Current vulnerability

Climate is an important component of the operating environment for Canadian mines. However, in recent years, mines across Canada have been impacted by extreme weather events, several of which are regarded to be consistent with climate change (Instanes et al. 2005; Furgal and Prowse 2008). This section describes some of the climatic conditions that mining operations in Canada have been exposed to, how they are changing, how operations are sensitive to these changes, and the adaptive strategies that have been employed to deal with them (Table 2).

3.1 Exposure-sensitivities

Transportation infrastructure Mining operations that depend on climate sensitive transportation networks (e.g. ice roads, air and water transport) are particularly susceptible to the warming trend noted across northern Canada (Prowse et al. 2009b). For example, the seasonal ice road network to the diamond mines in the NWT has been negatively affected by increasingly warmer winter temperatures experienced in recent years. The western and central Canadian Arctic experienced a general warming during the past 50 years of approximately 2 to 3°C (Prowse et al. 2009a). An increase in the number of days with thaw (defined as a day with snow on the ground when the daily mean temperature is above 2°C) was also recorded over the same time period (Smith 1998; Groisman 2003). In particular, 2006 was exceptionally warm during the winter and a bad year for the ice road, open for only 42 days because of unseasonably warm temperatures and shortening the operating season by nearly a month (the 2005 season was approximately 70 days). The financial costs

Table 2 Examples of exposure-sensitivities and adaptive strategies in the mining operation case studies

Case study	Exposure-sensitivities	Adaptive strategies
Diamond mining, NWT	• Warmer winter temperatures (Prowse et al. 2009a) and earlier spring melts (Smith 1998; Groisman 2003) have affected ice-roads used to transport fuel and supplies to mines (Scales 2006).	• Fly fuel and supplies to mines (higher costs) • Lighter-weight and amphibious machinery has been purchased to facilitate ice road construction earlier in the season. • Alternative ice road routes. • Improved operational efficiency to ship more loads over the ice road over a short window of time. • Construction of a seasonal overland route is being explored
Sand, limestone and dolomite quarries, SW Quebec	• Rising temperatures and warmer, drier summer conditions (Yagouti et al. 2006) have exacerbated dust emissions from sand, limestone, and dolomite quarries operating in the Montreal area in the summer.	• Curtail production to abide by dust emission regulations. • Invest in more rigorous dust suppression measures with added costs to operations.
Sodium sulphate mining, Saskatchewan	• In recent years fluctuations in water supply, seasonal precipitation and temperature (Sauchyn and Kulshthreshtha 2008) have led to limited water available to dissolve the mineral, which impedes the brining process.	• Diverting rivers, building dikes, and constructing water storage areas has improved the security of water resources.
	• Warmer winters (Sauchyn and Kulshthreshtha 2008) have reduced recovery rates, increased costs and delayed operations as frozen ground facilitates the retrieval process, which is usually conducted with heavy machinery.	• Increase water-use efficiency.
Base metal and gold mining, NW Ontario	• Reduced water levels caused by unseasonably warm, dry conditions have affected access to water resources (Brown et al 2006).	• Some mines have reduced operational intake of water and have found alternative sources.
Mining in Yukon Territory	• Torrential rains forced the Minto mine to release untreated water into the Yukon River system twice in two years (2008 and 2009). • Abandoned mines are sensitive to changing climatic conditions (e.g. permafrost melt, increased precipitation).	• Untreated water was released into the Yukon river with potential negative effects on fish and wildlife and the people who depend on them for subsistence.

of a reduced ice road season were significant. Freight that is not transported overland must be flown in to mine sites, with the expected increase in price that air travel brings. One of the most commonly transported items on the road is fuel—approximately 60% of trucks on the road are carrying fuel loads—and flying in fuel is expensive. In the shortened 2006 season, the Diavik diamond mine (owned by Rio Tinto) alone had to fly in 15 million liters of fuel. Another mining company operating in Nunavut at the time estimated it would cost an additional \$0.75 per kilogram or liter, to fly materials in rather than transport them by truck (Scales 2006). Using these figures, Diavik would have spent an extra \$11.25 m in flying in fuel that year. Warmer winter temperatures and earlier spring melts continue to be of concern to the diamond mine operators particularly because truck traffic on the ice road is expected to increase in coming years with expanding mining activity in the region.

Built infrastructure Most mine infrastructure has been designed assuming that the climate will remain stable. Consequently, in some instances extreme weather events have pushed mine infrastructure beyond its limits. There is increasing evidence that extreme weather events are changing in frequency and intensity, a consequence of anthropogenic forcing (IPCC 2007a). For example, changes in type, amount, frequency, intensity and duration of precipitation have been documented in Canada and internationally (IPCC 2007a; Lemmen et al. 2008). In the Yukon, torrential rains in August 2008 forced Sherwood Copper Corporation, which operates the high-grade copper-gold Minto mine located 240 km north of Whitehorse, to release untreated water into the Yukon River system. Some 350,000 cubic meters of water had to be siphoned out of the mine's water treatment plant and discharged. The waste discharge (.05 mg per litre) was higher than Yukon licence standards (.01 mg per litre). Ironically the water storage pond was designed to assure water availability throughout the year, given an expectation of occasional seasonal summer drought. The same rainfall also washed out a four kilometer section of the mine haul road leading to Minto Landing (Sherwood Copper Corporation 2008). The mine faced a similar situation in 2009 and again discharged untreated water into the Yukon River system higher than its Yukon license standards. The mine owner (now Capstone Mining Corporation) also asked permission from the Yukon water board to discharge waste water in spring 2010 (Thompson 2009).

Extraction The climate of south central Saskatchewan can provide ideal conditions for sodium sulphate extraction. Saskatchewan Minerals Incorporated's sodium sulphate mine located in Chaplin has remained successful since 1948 because of its ability to exploit favourable temperature, precipitation and runoff conditions to remove sodium sulphate from an 18 square kilometre alkali lake. Climate in the region, however, is highly variable. Recent trends and future climate projections include lower summer stream flows, falling lake levels, retreating glaciers, increasing soil and surface water deficits, greater frequency of dry years, and warmer winter temperatures (Sauchyn and Kulshthreshtha 2008). In recent years fluctuations in water supply, seasonal precipitation and temperature have had negative implications for the mine's operations. Low amounts of spring runoff and a lack of precipitation have led to limited water available to dissolve the mineral, which impedes the brining process. In long-term drought situations, production has been reduced to a virtual standstill until adequate precipitation or runoff has been received. In addition, warm winters have reduced recovery rates, increased costs and delayed operations as frozen ground facilitates the retrieval process, which is usually conducted with heavy machinery.

Daily operations In Quebec, dust emissions from sand, limestone, and dolomite quarries operating in the Montreal area have been exacerbated by rising temperatures and warmer, drier conditions in the summer. A 0.5°C and 1.2°C increase in mean annual temperatures has been recorded in southwestern and south-central Quebec between 1960 and 2003 and warming has been most pronounced in the winter and summer (Yagouti et al. 2006). Dust control measures are employed by all companies and are especially important in hot, dry conditions. For most mining operations, this involves spraying water at mine sites to suppress the dust, although some of the larger operators have shelters to cover storage and processing facilities. Dust control was a particularly important issue for those mines operating close to urban areas, as municipal regulations strictly control the amount of atmospheric dust loading that occurs. Warmer, drier summers have resulted in some mining operations curtailing their production to abide by dust emission regulations and/or investing in more rigorous dust suppression measures with added costs to operations.

Post-operational phase In most cases, mine infrastructure (e.g. tailing ponds, embankments, spoil heaps, berms) has been designed assuming climatic stability. The risk of structural failure due to the forces of expected future climatic changes is therefore of great concern at several abandoned or orphaned mines across Canada. Currently there are already instances where abandoned mines have been affected by changing climatic conditions. The Clinton Creek asbestos mine in Yukon, for example, was operated by the Cassiar Asbestos Corporation Ltd. from October 1967 until August of 1978. The mine had three open pits, located on the south side of Clinton Creek, and created approximately 60 million tonnes of waste rock, which have blocked the creek and formed Hudgeon Lake. During its short life, the mill discharged nearly 10 million tonnes of tailings to the Wolverine Creek valley. When the mine was planned neither seasonal frost nor permafrost thaw potential were considered to be significant. The possibility of climate change was not considered and it was thought that permafrost would remain frozen forever. The tailings dumps have since failed and formed two lobes, blocking the flow of Wolverine Creek. The creeks have eroded both the tailings piles and waste rock dumps, and fish habitat of the upper Clinton Creek and Wolverine Creek have been destroyed. The federal Government has paid for gabion stone (mesh cage) beds to stabilize the waste rock piles and allow water flows to resume in the creek. Cost estimates to stabilize the property range from $17 million to $35 million.

3.2 Adaptive strategies

Changes in climate have already exacerbated some pre-existing climate sensitivities for mining operations, requiring mines to undergo some level of adaptation. As per Smit and Skinner (1999), in most cases adaptations can be described as either, *reactive* and *ad hoc* in nature, or *strategic* and *pro-active*. The type and nature of response to deal with climate change exposure-sensitivities differs among mining operations and regions and is influenced by a variety of climatic and non-climatic factors.

Reactive adaptive strategies To date, most adaptive strategies employed by mining operations have been *reactive* and *ad hoc* to deal with extreme climatic events. These reactions have resulted in financial costs to companies and/or to the environment. Examples include: diamond mining companies operating in the NWT initially reacted to a shortened ice road season by using expensive air transportation to bring fuel and supplies to the mines. This reactive adaptive strategy worked as a short-term substitute for the ice road but is not financially sustainable. Sherwood Copper Corp. reacted to torrential rains that breached their water storage pond by releasing untreated water into the Yukon River system with potential negative effects on fish and wildlife and the people who depend on them for subsistence. It appears that the mining operation has done limited, if any pro-active planning to prevent a repeat event. In summer 2009 Sherwood Copper Corp. applied to the Yukon Water Board for an emergency permit to discharge 10,000 cubic meters of runoff and waste water a day from the mine site in order to create room in case of heavy summer rains (the same application included another order to cover the 2010 spring runoff as well);

in 2005 a number of mining operations located near Marathon, Ontario were forced to significantly reduce operational intakes of water and find alternative sources, because of reduced water levels caused by unseasonably warm, dry conditions in their watershed (Brown et al. 2006); and small quarries operating in the Montreal region have sometimes curtailed production during hot, dry summers to avoid fines for dust pollution.

Alternative transportation routes Diamond mining companies in the NWT have now initiated *strategic, pro-active* adaptation planning to deal with the effects of warming winter temperatures and earlier spring thaws on the ice road network. In the short-term, new lighter-weight and amphibious machinery has been purchased to facilitate ice road construction earlier in the season, alternative road routings have been developed, and operational efficiency has been improved to ship more loads over the ice road in a shorter window of time. Long-term alternatives to the ice road are also being explored. Construction of a seasonal overland route and utilizing the proposed Bathurst Port and Road Project are two of the options currently being investigated.

Flexibility The process of sodium sulphate extraction employed at the Chaplin mine in Saskatchewan has been strategically adapted to variability in local climate. This mine has adopted a number of practices and built specialized infrastructure to ensure its survival. The security of water resources has been improved by the development of diversions from the Wood River to Chaplin Lake via the Chaplin Creek. In addition, the mine has built water storage areas, further improving supply security and allowing for increased management of water flow into the lake. A system of dikes allows for further control of water levels across the lake, increasing management options and ensuring optimal brine concentrations while improving water-use efficiencies. Having alternative water sources and multiple management options allows the mine to be flexible and cope with fluctuations in precipitation and spring runoff.

4 Future vulnerability

Based on current climate trends and expected future GHG emissions scenarios, it is expected that climate change will continue in the future with further implications for environments and the mines that operate in them. How climate change is experienced will continue to be influenced by the location and type of mine and as a result, mines will be faced with a variety of exposure-sensitivities based on the local conditions under which they operate. This section builds on knowledge of current exposure-sensitivities and adaptive strategies together with information about the climate and non-climate variables identified as being important to the case studies to provide insights on future vulnerability.

4.1 Future exposure-sensitivities

Transportation infrastructure Mining operations located in permafrost zones and that depend on climate-sensitive transportation networks are expected to continue to be affected by changing climatic conditions (e.g. Instanes et al. 2005; Holubec 2007; Furgal and Prowse 2008). Remote mines without year-round ground transportation links will be particularly vulnerable. For northern Canada, climate models indicate increases in annual amounts of precipitation, increased frequency and magnitude of extreme climate events, and warmer temperatures particularly in the summer and winter (Lemmen et al. 2008; Prowse et al. 2009c). Land-based transportation routes could face risks from melting permafrost including road embankment instability and accelerated erosion. Ice road networks will undoubtedly also be compromised, as a warming climate will make it more difficult to maintain sufficient ice thicknesses to support heavy traffic flows.

Transportation infrastructure that services Ontario mines may also be at risk from future changes. Chiotti and Lavender (2008) note that the vulnerability of critical transportation infrastructure (especially road and rail) to extreme weather events is an issue of "greatest concern". Similarly, a report prepared on the vulnerability of road networks to climate change in the City of Greater Sudbury identified "potentially major vulnerabilities" to road drainage infrastructure (Dennis Consultants 2008).

Built infrastructure Mines are typically designed to cope with climatic events of a certain recurrence interval (e.g. a 1 in 100 year storm event) and within specified climatic parameters. Expected future climate change thus has the potential to affect buildings and built structures, slope stability, tailings and water retention structures, and site hydrology in some regions of Canada. For example, buildings erected on thaw-sensitive land could see their foundations settle and shift—and in the worst case collapse—as permafrost melts, increasing maintenance expenditures and causing potential operational delays. Extreme weather events could also increase susceptibility of buildings to damage. Extreme flooding, ice storm and wind events already cause significant weather related damage to infrastructure (Auld and MacIver 2006) and in some regions these events are expected to increase. Infrastructure built on or near steep slopes will also need to consider the increased susceptibility of those slopes to slumping and sliding as underlying frozen material loses cohesion due to melt. Examples of these considerations are already being documented in northern communities and it seems only a matter of time before mining operations could become similarly affected.

There could also be hazards associated with waste rock piles and tailings retention structures (e.g. Instanes et al. 2005; Holubec 2007; Furgal and Prowse 2008). Some tailings retention structures in the north, for example, depend on frozen conditions for the lifetime of the structure. The implications of a warming climate are that these dams could lose their structural integrity over time, possibly leading to failure. At the very least, warming air temperatures could result in increased maintenance and operational costs to keep the embankment frozen. In the worst case, tailings dam failures could spill mine wastes (including acid generating wastes) and contaminants into the environment. Extreme rainfall, rain-on-snow events and rapid melting of the snowpack within a watershed could also overwhelm site drainage and diversion structures, causing excess runoff to tailings impoundments. This could lead to saturation, erosion or rapid rise in water levels and overtopping (ICOLD 2001). In the context of such projections, release of acid rock drainage and other contaminants to the environment is a concern. Slope stability and the integrity of engineered berms are also vulnerable to extreme precipitation (Chiotti and Lavender 2008). Erosion of the dam slope or gullying at the base of the impoundment structure could occur, causing weaknesses in the dam and increasing its risk of failure. Saturation of the impoundment structure causing piping, slumping or failure is also a risk (ICOLD 2001). This would be a major concern in the Arctic where remoteness will constrain clean-up operations and the cold climate results in slow natural decomposition of pollutants. Undoubtedly, there would also be repercussions for corporate image. Companies might also have to give up some or all of the financial assurance they provide for surety against environmental incidents.

Changes to regional temperatures and precipitation regimes could also affect mine site hydrology and water balance. At some operations, runoff is collected in a basin or drawn from rivers to be used in mine operations (e.g. for mineral processing). Increased incidences of hot, dry summers, for example, could alter water availability. Increased temperatures could also lead to increased evaporation from tailings ponds, potentially exposing raw tailings to sub-aerial weathering. Similarly, passive contaminant reduction systems (e.g. wetland filtration) could be at risk if ground cover dries up and re-exposes metals and contaminants in the ground below.

Post-operational phase A number of possible future exposure-sensitivities are particularly important for mine closure planning. Structures left on-site after closure will need to withstand changing climatic conditions long into the future. Similarly, already abandoned tailings ponds or waste rock stacks may not have been designed for the full range of these changing climatic conditions and will need to be monitored and retrofitted accordingly. Left abandoned and un-checked, some of these sites could pose significant risks to the environment and surrounding communities, especially in light of changing climatic conditions. It has often been the case that abandoned mines become the public's responsibility as companies rise and fall at the hands of global mineral markets. This can result in high financial burdens for government agencies. For example, a conservative estimate of the cost to remediate the site of the abandoned Faro Zinc Mine in the Yukon is approximately $500 million CDN with long-term monitoring of the site extending into the next century (L. Craig, personal communication, 15 July 2008).

4.2 Future adaptive capacity

The ability of mining operations to adapt to future climatic change is conditioned by a number of factors including access to engineering solutions, knowledge of potential future climate change, expert resources, incentives to address long-term climatic hazards, and priority of other non-climate issues (e.g. global markets, costs of production, labour needs). Whether or not mining operations choose to invest in climate change adaptation planning will depend in part on the specific mining operation and also on the regulators who could mandate that climate change is considered in mine development and closure plans.

Engineering solutions In many instances the technologies and engineering strategies necessary for adaptation to climate change in the mining sector already exist (e.g. thermosyphons, enhanced structural design, strengthened holding facilities, alternative transportation routes, etc.). For example, in operations where maintaining frozen conditions is necessary, thermosyphon technology may be appropriate. Thermosyphons are self-powered refrigeration devices that are used to keep permafrost cool. The Ekati and Diavik diamond mines already use them to help maintain thermal integrity of various structures and this technology could be employed at other operations to help maintain structural integrity in light of degrading permafrost conditions. Similarly, tailings cover can be modified in other ways to ensure the materials below ground stay frozen, and ground-based transportation networks can be built in ways to minimize disturbance to the frozen soil layers below. Insulation of the surface (e.g. using thicker gravel pads) and clearance of snow (to promote colder ground temperatures) are some examples (Couture et al. 2003). These modifications will be especially important where frozen conditions are essential to the integrity of structures and designs. In other cases, holding ponds, berms and other containment infrastructure can be strengthened to withstand more frequent extreme events and expected future increases in precipitation during the life of the mine and beyond.

Climate information To effectively deal with potential future climate change, engineering designs can incorporate information from past experiences with change and expected future change into their calculations. ‘Climate forecasting’ is an evolving area of climate change science but has yet to produce the detailed regional data needed for site-specific engineering design. Climate models provide useful, albeit generalized, pictures of predicted changes, but there is a need for their further refinement including better regional climate models. Decision makers responsible for designing, building, and maintaining mine infrastructure need to know what climate conditions mines are, and could be faced with in the future, and what engineering techniques need to be adopted to manage these changes.

Expert resources Specialists play critical roles in how mines are designed and if future climate change is considered. In mine development expert personnel are hired to conduct the specialized tasks related to building a mine, including its design and construction. For example, there are no standardized regulations for building on permafrost so it is up to the individual contractor to make their own design assertions. Some consultants, contractors, engineers, and regulators who work on mining projects have made strides in climate change adaptation planning. They have reported on adaptation issues and even incorporated climate change adaptation into their work (e.g. Holubec 2007; Hayley and Horne 2008; Hayley and Proskin 2008).

Experience drives adaptation Where action has been taken to adapt to changing climatic conditions it has largely been reactionary in nature or in response to past experiences with climatic events. Perhaps not surprisingly, there were noted differences in the attitudes of respondents who work ‘on the ground’ at mine sites, and those who work in ‘office’ setting administrative and managerial roles, as reported in interviews here and in surveys by Ford et al. (2010c, in press). The former tended to view climate change as a more pressing issue for mine operations, likely because of greater day-to-day interaction with climate at an operational level. Senior managers were more often preoccupied with short-term problems rather than long term climate change adaptation planning. After all, most mines have relatively short operational life spans. Mine managers are often focused on short-term objectives and do not see a need to plan 50–100 years into the future. Large investments of time and resources (e.g. improved infrastructure) into climate change adaptation thus seem inappropriate to some mining companies. This is cause for concern as new mines will inevitably come on-line and operate well into the future, and mine closure planning will need to consider potential future climate change.

Role of regulators In most instances, long term adaptation planning has been largely voluntary. That is to say, few legislative repercussions exist for operations that do not include climate change in planning decisions. For example, there are (as yet) no widespread legal obligations to consider climate change in mine planning or in mine closure plans. There are, however, isolated cases when climate change has been included in environmental impact assessment processes for mines (e.g. Carmacks Copper Mine, Yukon). Furthermore, in recent years companies have been required to post security deposits to cover the costs of site remediation should the mine be abandoned.

5 Conclusion

The case studies were taken from diverse geographic settings and each mine was unique in terms of its climate vulnerabilities. However, a number of key findings are evident across the case studies:

i) **Mines in the case studies are affected by climate events that are indicative of climate change, with examples of negative impacts over the past decade**. The mine sites have been designed to operate effectively within particular climatic parameters and to manage events of a certain recurrence interval (e.g. a 1 in 50 year, or 1 in 100 year storm event). Yet climatic events that exceed mine design parameters sometimes occur and have had dramatic consequences for mine operations and the environment. The last decade, for example, provides a number of instances where mine operational capacity has been compromised by climatic events; events which are expected to become more intense and frequent with climate change.

ii) **Most mine infrastructure has been designed assuming that the climate is not changing**. Mines are often designed to cope with events of a certain recurrence interval and within specified climatic parameters. In some instances, extreme weather events have pushed mine infrastructure beyond its limits. These extreme weather events are predicted to become more common with climate change. Climate change thus has the potential to affect buildings and built structures, transportation networks, slope stability, tailings and water retention structures, and site hydrology in some regions of Canada. In instances where new hazards have already emerged during mine operation, adaptation has usually been *reactive* and *ad hoc* in nature. There are very few examples in the case studies where new hazards have been identified *a priori* and *strategic* adaptation strategies developed; it usually first involved infrastructure damage or constrained operational capacity before investments in adaptation occurred. Currently, mining operations are for the most part not making investments to climate-proof infrastructure because in many cases the affects of climate change are not immediate and are also uncertain. There is a need for government regulation of mine infrastructure and closure planning to ensure that all mines are designed to deal with the affects of current and expected future climate change.

iii) **Most industry stakeholders view climate change as a minor concern**. In the case of some recently developed mines climate change has been viewed as both a potential risk and opportunity for their operations. For some mine sites located in areas especially sensitive to climatic conditions (e.g. in the Northwest Territories and Yukon), climate change has been noted to negatively affect various aspects of mine operations (e.g. ice road networks) and elsewhere has been noted to have potential benefits (e.g. decreased heating costs, longer exploration and operating seasons). However, most respondents involved in mine administration and managerial roles (24 of 31 respondents, 77%) viewed climate change as only a minor concern, particularly when compared to more pressing issues such as meeting regulatory and human resource requirements, and managing fluctuating market conditions. These results are consistent with the survey reported by Ford et al. (2010c, in Press). A number of factors may explain the ranking of climate change by mining practitioners as a relatively minor issue. First, knowledge of the nature, magnitude and speed of climatic change is poorly understood in the sector. Very few participants were aware of scientific or industry publications on climate change or what changes were projected to occur in their region. Even for mines where climate change was assessed in the environmental assessment process, knowledge of climate change by mine site employees was often limited. Vulnerability is not just a matter of the likelihood of physical structures to be adversely affected by climatic events—it is also reflective of the attitudes, expectations and knowledge of mining practitioners in regards to climate change. Naturally, poor understanding of the issue will exacerbate vulnerability; the mining sector is unlikely to adapt to something that it does not first understand. Second, many mining operations have a limited life span, dictated largely by the size of the deposits being mined. Several practitioners view climate change as a risk decades in the future and therefore of limited immediate importance. Third, for small mines in particular, the focus is on meeting short-term customer requirements and there are often limited resources and incentives available to contemplate future challenges such as climate change.

iv) **Limited adaption planning for future climate change is underway**. The absence of planning is further reinforced by the apparent high cost of implementing many adaptations and lack of government regulation requiring mines to develop adaptation plans. In many instances, adaptation options are available to manage future climate change hazards but the cost of these options is sometimes prohibitive, especially for small profit margin mining operations. Limited planning for climate change is a cause for concern given the climate sensitivity of a number of current mining operations, as climate change could compromise mine operational capacity, result in periods of reduced production, and force companies to make reactive and possibly costly adaptations in order to continue operating in the future.

v) **Significant vulnerabilities exist in the post-operational phase of mines**. The risks resulting from not sufficiently planning for climate change extend beyond the mining operations themselves and on to the natural environment and surrounding human communities. The production stage is only one portion of the life cycle of many mines. Most current mines have a relatively short life span and are not expected to be operating when the most severe effects of climate change manifest themselves in the future. From an operational standpoint, these mines do not necessarily need to be designed to accommodate changing climatic conditions for the near term. However, climate change could present potentially serious hazards for mines in the post-operational and closure stages. If mine infrastructure is designed only according to design criteria relevant to the current climatic regime, the risk of structural damage and/or failure due to the forces of future climate change becomes pronounced. An estimated 27,000 orphaned or abandoned mines currently exist in Canada and there has been little research done on the impacts of climate change on abandoned mines and mine rehabilitation projects (NRCan 2007b). What will happen to operating mines after decommissioning in a changing climate is also currently not well understood.

The manner in which the mining industry responds to the challenges brought on by climate change has important implications for the national economy. Climate concerns are a central fact of business life and adapting to the reality of climate change is in the best interests both of mining companies and communities whose wellbeing is intractably tied to the success of the industry. To date, the response to current and expected future climate change has been slow, but the same can be said for other sectors of the Canadian economy. Where there has been response it has largely been the result of learning through experience (e.g. forestry (Ogden and Innes 2007)).

Some degree of future climate change is now inevitable. The Canadian landscape will be altered and there will be challenges for mining and other industries. Industry is a vital component of Canadian social and economic life with considerable experience and vested interest in addressing climate related issues. In Canada, there are a number of mining companies operating in multiple locations, a strong mining service sector, and institutions (e.g. universities, research organizations, government offices) similarly working to advance the sector. The potential for cooperatively developing effective adaptation strategies is thus substantial. Collaboration among mining companies, regulators, scientists and other industry stakeholders to develop practical adaptation strategies that can be mainstreamed into existing mining operations will greatly enhance chances of success. There now exists a real opportunity for Canadian companies to become leaders in climate change adaptation. The lessons that are learned in Canada could soon be applied around the globe.

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