Costs of Climate Change on the Prairies

Final Report

31 March 2023

All One Sky Foundation

ClimateWest

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ClimateWest

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HIGHLIGHTS

Information on the economic consequences of climate change is increasingly being demanded by decision-makers as they contemplate how to respond. A key piece of economic evidence used to make the business case for action are the costs that result from allowing climate change to continue unabated and without new adaptation. Both economists and adaptation practitioners often refer to these costs as the "costs of inaction". Estimates of the costs of climate change are being used by decision-makers to inform the overall scale of investment in adaptation, the prioritization of risks, and the selection, timing and sequencing of specific adaptation options, as well as the distribution of costs and adaptation benefits.

While climate change is anticipated to bring some benefits for the Prairies, the total economic impact is projected to be overwhelmingly negative and significant. Under a high future climate scenario, direct economic losses across all three provinces are estimated at $15.7B and $37.4B per year (2020 dollars) by the 2050s and 2080s, respectively. In both time periods, over half these losses result from impacts in Alberta, which has the largest population, asset inventory and economy of the three Prairie provinces. However, on a per capita basis, the largest annual losses in both future time periods are expected to occur in Manitoba ($2,235-$3,680 per person), followed by Saskatchewan ($1,875-$3,330 per person), then Alberta ($1,300-$2,230 per person).

The scale and direction of projected economic losses directly attributable to climate change vary by climate-sensitive sector:

Losses of $11.5B (2050s) to $28.9B (2080s) annually from public health impacts caused by higher temperatures, deteriorating air pollution and increased cases of Lyme disease.

Losses of $0.7B to $1.8B annually from reduced worker productivity due to higher temperatures.

Losses of $1.6B to $3.8B annually from damages to transportation infrastructure and associated delays in the movement of people and freight.

Losses of $0.6B to $1.1B annually from damages to electricity transmission and distribution infrastructure and changes in electricity demand to heat and cool buildings.

Losses of $1.2B to $1.8B annually from damages to building structures and contents resulting from river and stormwater flooding.

Increases in farmland values of $3.4B to $4.3B annually from rising productivity due to seasonal warming, a longer growing season and increases in total annual precipitation.

Loss of $3.4B annually in projected Gross Domestic Product (GDP) for Prairie provinces, the Yukon and Northwest Territories over the period 2010-2080 from reduced timber supply.

The estimated costs of climate change for the Prairies are almost certainly larger than the losses presented above. There are several key gaps in our current state-of-knowledge, including failure to account for cascading and compounding impacts across sectors and climate impact-drivers, the loss of key service flows provided by infrastructure (e.g., drinking water, power, housing, etc.), impacts of extreme weather events, impacts to some key sectors (e.g., primary extractive industries, water resources and tourism), and persistent impacts to economic growth.

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1 INTRODUCTION

Climate change is already causing impacts with economic consequences today and will do so increasingly in the future. These impacts affect different aspects of the built and natural environment, public health and safety, labour productivity, and the economy. Building resilience and adapting in our urban centres to unavoidable climate change has been conservatively estimated to require an annual investment of 0.26% of GDP[1], which equates to about $10.6 billion for the six largest metropolitan areas on the Prairies over the next 10 years[2]. Given the potential magnitude of climate adaptation investment costs, there is a need to provide decision-makers—who face limited human and financial resources—with defensible economic information on projected costs and associated benefits to support adaptation investment decisions. A key piece of economic information used to persuade senior leadership and elected officials of the need and urgency to allocate resources to adaptation planning is the future costs that result from allowing climate change to continue unabated and without further planned adaptation (EEA, 2007; and Ackerman and Stanton, 2011)[3]. These costs are commonly referred to as the "costs of inaction" by both economists and adaptation practitioners. This information can be used to:

- Quantify the overall scale of the challenge presented by the physical risks of climate change and convey the urgency for action;
- Inform the distribution of economic impacts across population groups, assets, climate-sensitive sectors and regions;
- Support the prioritization of climate-related threats and opportunities;
- Support the selection, timing and sequencing of specific adaptation options; and
- Guide the required level of investment in adaptation.

Indeed, the first key message in the costs and benefits chapter of the National Issues 2021 volume of Canada in a Changing Climate states: "*Faced with limited resources and competing priorities, economic analysis can help decision-makers clarify trade-offs, and make the case for allocating resources to climate adaptation and specific actions, by providing information on the costs and benefits of different choices*."[4]

Several studies have investigated the costs of climate change for a selection of climate-sensitive sectors on the Prairies, and for Canada, with regionally disaggregated results covering the Prairies. Two detailed assessments have also been completed for the City of Edmonton and the City of Calgary. The goal of this report is to synthesize this literature into a single compendium of the costs of climate change for the Prairies reflecting the current state-of-knowledge.

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[1] IBC and FCM, 2020: Investing in Canada's Future: The Cost of Climate Adaptation at the Local Level, Final Report, February 2020.

[2] The total 10-year investment in adaptation across the Prairies (census metropolitan and non-metropolitan areas) at 0.26% of projected GDP is about $17.6 billion.

[3] EEA, 2007: Climate change: the cost of inaction and the cost of adaptation. EEA Technical Report | No 13/2007, European Environment Agency (EEA), Copenhagen, Denmark, 67 pp; and Ackerman, F. and Stanton, E., 2006: Climate Change – the costs of inaction. Report to Friends of the Earth England, Wales and Northern Ireland, Global Development and Environment Institute, Tufts University, Medford, Massachusetts, 38 pp.

[4] Boyd, R. and Markandya, A., 2021: Costs and benefits of climate change impacts and adaptation; Chapter 6 in Canada in a Changing Climate: National Issues Report, (Eds.) F.J. Warren and N. Lulham; Government of Canada, Ottawa, Ontario [https://changingclimate.ca/national-issues/chapter/6-0/]

2 INTERPRETING THE COSTS OF CLIMATE CHANGE

There is a wide spectrum of terms used to characterise the economic consequences of climate change impacts and adaptation – e.g., direct costs, indirect costs, secondary costs, ripple-effects, macroeconomic impacts, private costs, social costs, externalities, side-effects, co-benefits, co-impacts, ancillary costs, market impacts, non-market impacts, tangible effects, intangible effects, net costs, and welfare costs. The range of terms, many of which overlap and are used interchangeably, can lead to confusion among practitioners and decision-makers. It can also impede efforts to compare or aggregate estimated costs and benefits. Furthermore, quantifying the economic consequences of climate change across the range of potentially impacted human systems and the environment requires what are best described as multi-model, multi-sector approaches. Typically, modelling approaches vary across climate-sensitive sectors, but most analyses are performed within a common analytical framework that combines socioeconomic information with climate scenarios.

For clarity when interpreting the results presented below, this section first describes this common analytical framework and second defines key cost and benefit terms as used in the remainder of this document.

2.1 Analytical framework for estimating economic impacts

Regardless of the specific sectoral modelling approach used, best practice involves constructing estimates of the costs of climate change in three steps. These steps are illustrated in Figure 1 using an example of premature mortality due to heat stress from a national climate change health study recently completed for the Canadian Institute of Climate Choices[5].

1. The first step involves: estimating current economic impacts to provide a baseline against which to compare future costs (2025 in this example), based on current exposures (e.g., the population at risk), current vulnerabilities (e.g., the baseline natural mortality rate in the population), and current climate conditions (e.g., mean daily temperature between May-September over the period 2011-2040). This generates point **A** shown on the left-hand-side of Figure 1.
2. The second step involves: estimating economic impacts in the future (in this example, through 2055) accounting for projected socioeconomic change—that is: growth in exposures (increased population at risk), growth in real prices and wealth (higher healthcare unit costs and higher willingness-to-pay of individuals to avoid illness or risk of death), and changes in vulnerability (changes to the natural mortality rate in the population as the age distribution and health care provision changes). But, during this second step, the climate is held constant at baseline levels. In effect, current climate conditions are overlaid on a future society, such that the change in economic impact over time is driven solely by socioeconomic change. This step generates the path to point **B** in Figure 1.

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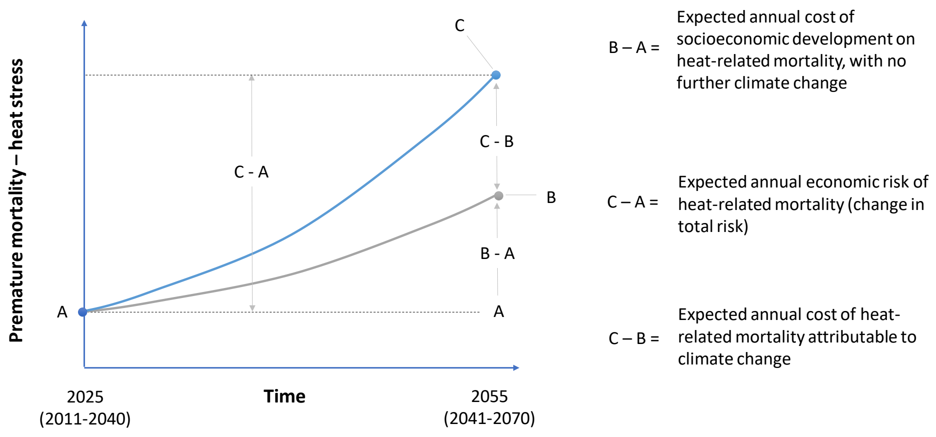
[5] Boyd, R., Eyzaguirre, J., Poulsen, F., Siegle, M., Thompson, A., Yamamoto, S., Osornio-Vargas, Erickson, A., and Urcelay, A., 2020: Costing Climate Change Impacts on Human Health Across Canada. Prepared by ESSA Technologies Ltd. for the Canadian Institute for Climate Choices.

3. The third step involves: overlaying projected future climate change on top of the projected future society. This is shown as the path to point **C** in Figure 1, which defines the change in total economic risk from today (i.e., 2025).

Application of this framework enables isolation of the incremental impact of further climate change beyond today (given by C – B) from the influence of projected socioeconomic change (given by B – A). Specifically, the estimated economic impacts defined by C – B measure the heat-related mortality costs attributable to further climate change. Importantly, the height of point C defines the costs of climate change, which is the Reference Case for analyzing the economic performance of adaptation options. Indeed, when it comes to introducing adaptation action in subsequent cost-benefit analysis, interest lies in the extent to which adaptations can reduce C back towards A and below.

Several of the studies summarised below fully adopt this framework—for example, the results for public health, workforce, and electricity demand for space heating and cooling, as well as the City of Calgary and City of Edmonton case studies. Other studies summarized below (e.g., for infrastructure, flooding of building) do not incorporate socioeconomic change (Step 2)—overlaying projected future climate change on today's society. These studies will understate the total economic risks presented by climate change and the pool of potential adaptation benefits.

Figure 1: Methodological steps to estimate the costs of climate change – illustrated using example of estimating heat-related mortality in 2050



Source: Boyd, Eyzaguirre, Siegle, et al. (2020)

2.2 Types of costs

Three broad types of economic consequences are reference below, though all three are not estimated by each study:

1. **Direct-tangible costs**. These costs arise from the direct biophysical impacts of climate impact-drivers, such as damage or disruption, to (**tangible**) goods and services that can be traded in a market and thus have an observed price as a basis for monetization (e.g., costs incurred to repair or replace damaged homes, the medical treatment costs for heat stress, etc.). This also includes

business interruption costs, the costs of evacuation and temporary accommodation, etc. as a result of the direct damages caused by flooding[6].

2. **Direct-intangible costs**. These costs arise from direct biophysical impacts to (**intangible**) items not bought or sold in a traditional market and thus with no readily observable price as a basis for monetization (e.g., ecosystem services, stress or pain levels, travel delays, premature death). Economists have developed multiple techniques to 'shadow price' these intangible (or non-market) impacts (e.g., the Value of a Statistical Life used to price the risk of premature death in a population). Below, direct-intangible costs and welfare losses are used interchangeably—the latter term is more commonly used by economists.
3. **Secondary-tangible costs**. These costs arise from the ripple effect of the direct **tangible** impacts on the wider economy as subsequent spending (both indirect and induced) is affected. Indirect impacts result from changes to upstream inter-industry purchases by the directly impacted economic sector(s). Induced impacts result from changes in the production of goods and services in response to changes in consumer income and household expenditures driven by the direct and indirect impacts as they ripple through the economy. Below, the most commonly measured secondary-tangible costs are reductions in projected gross-domestic product (GDP).

Regarding these secondary-tangible costs, they are sometimes erroneously viewed as a net gain for society. While some sectors, like remediation services and construction, might benefit from increased demand for clean-up and restoration services following an extreme weather event, this benefit should be viewed more as a transfer of resources towards sectors responding to the event and away from those that suffer damages as a direct result of the event. The costs incurred to restore assets to their pre-event state thus represents an "opportunity cost"—the opportunity cost refers to the forgone benefits from transferring expenditures away from the activities that would have occurred in the absence of damage from the climate-induced event[7]. In short, these expenditures would not have been incurred in the absence of climate change impacts.

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[6] The flood assessment literature refers to these latter costs as "indirect losses". However, the economic literature tends to treat them as direct, tangible costs to distinguish them from wider indirect and induced (secondary or cascading) impacts on the economy.

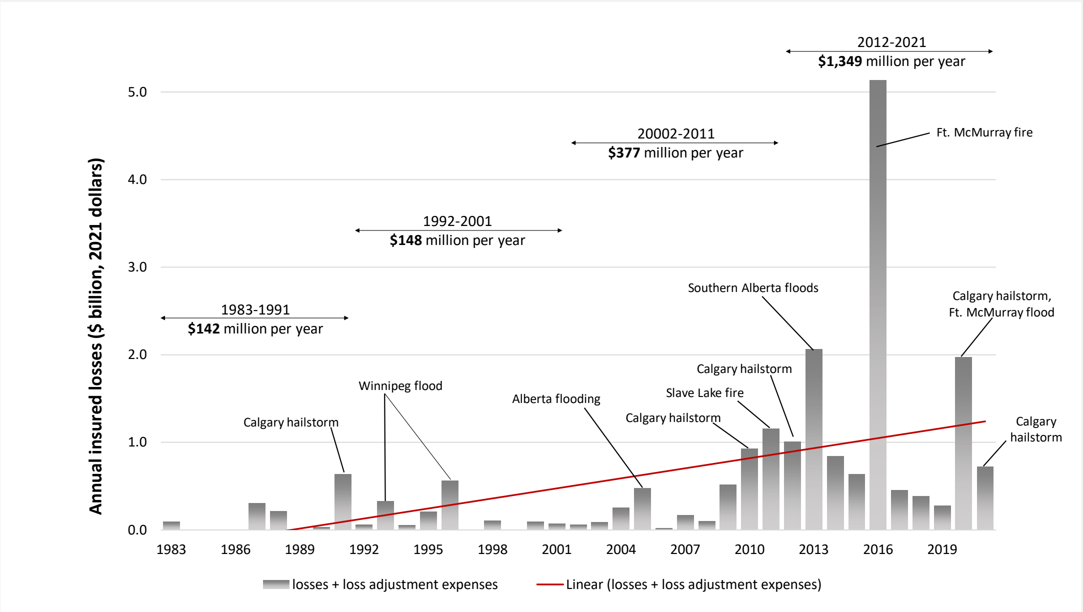
[7] For a more detailed explanation as to why secondary-tangible costs should be treated as opportunity costs (i.e., net losses and not net gains), see Kousky, C., 2012: Informing climate adaptation: a review of the economic costs of natural disasters, their determinants, and risk reduction options. RFF DP 12-28, Resources for the Future, Washington, DC, 62 pp; or Hallegatte, S., 2013: The indirect cost of natural disasters and an economic definition of macroeconomic resilience. Impact Appraisal for Sovereign Disaster Risk Financing and Insurance Project: Phase 1 Public Finance and Macroeconomics, Paper 3. Sustainable Development Network, Office of the Chief Economist, The World Bank, Washington, DC, 35 pp.

3 HISTORICAL COSTS OF WEATHER EXTREMES

Before reviewing the projected economic consequences of climate change for the Prairies, information on the costs of past severe weather events is summarized for context. Extreme weather events—such as heatwaves, droughts, wildfires, flooding and strong storms—are the face of climate change on the Prairies. Indeed, three of the five most costly events in Canada have occurred on the Prairies—all in Alberta. Moreover, losses from extreme weather events have been rising since the early 1980s when the insurance industry in Canada began to track payouts (as evident from the solid red trend line in Figure 2). Over the last decade, losses on the Prairies averaged $1,349 million year; in contrast, in the previous decade annual losses averaged $377 million and in the decade before that, $148 million annually. It must be stressed that insured losses only represent a fraction of total tangible costs—tangible costs to homeowners and government from extreme weather events can be 3-4 times insured losses. Intangible costs and secondary costs are also not captured by insured losses. The total economic consequences of extreme weather events on the Prairies are thus significantly higher than indicated by the loss data in Figure 2.

Studies on the attribution of extreme weather events on the Prairies indicate that climate change is increasing the likelihood of certain types of events occurring and may be playing a role in the rising trend in losses shown in Figure 2[8]. This upward trend in losses is expected to continue for the coming decades with climate change anticipated to intensify some types of extreme weather events in the future.

Figure 2: Trends in insured losses and loss adjustment expenses from extreme weather events on the Prairies 1983-2021 (2021 dollars)



Source: data from Insurance Bureau of Canada (IBC) Fact Books, PCS, 2022

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[8] Zhang, X., Flato, G., Kirchmeier-Young, M., et al., 2019, Changes in Temperature and Precipitation Across Canada; Chapter 4 in Bush, E. and Lemmen, D. (Eds.), Canada's Changing Climate Report, Government of Canada, Ottawa, ON., pp 112-193.

4 PUBLIC HEALTH

Climate change is already adversely affecting the health of Canadians, with the consequences projected to worsen with further climate change[9]. Climate change impacts our health by: altering exposures to extreme heat events, floods, droughts and other extreme weather phenomena; through the expansion of vector-, food- and water-borne infectious diseases; deterioration of air and water quality; and increased stresses to mental health and psychosocial well-being.

Estimates of the future economic consequences of three public health hazards anticipated to worsen with further climate change are available for the Prairies: exposures to ground-level ozone, high temperatures, and Lyme disease. The economic consequences of exposure to historic wildfire smoke events in Canada has also been estimated, with results available for the Prairies. In this section, the methods used to generate the economic impacts of these hazards is briefly described and presented along with the results.

4.1 Air quality—ground level ozone

Changes in the climate will affect the air we breathe[10]. Climate change is altering weather patterns, which in turn are affecting levels of outdoor air pollutants, such as ground-level ozone (O_3) and fine particulate matter ($PM_{2.5}$). Warmer air temperatures are conducive to the formation of O_3. Climate change is also anticipated to alter weather conditions that influence $PM_{2.5}$ concentrations in the atmosphere from natural sources—plants, wildfires and dust. Poor air quality negatively affects our respiratory and cardiovascular systems, and can cause premature deaths, hospital visits, acute respiratory symptoms (e.g., coughing, shortness of breath, irritations, inflammatory response of the mucous membranes, and reduced respiratory function), and lost workdays.

Changes in the climate—specifically changes in minimum and maximum temperatures, changing precipitation patterns, and increasing concentrations of atmospheric carbon dioxide (CO_2) that boost plant growth—are also projected to increase levels of airborne allergens (so-called “aeroallergens”). These changes will influence the prevalence and severity of allergic disease in the general public. Higher pollen levels and longer pollen seasons can increase allergic sensitization and asthma attacks.

4.1.1 Approach

Boyd et al. (2020) used the Health Canada’s Air Quality Benefits Assessment Tool (AQBAT) 3.0 to estimate the mortality and morbidity impacts for Canada associated with changes in ground-level O_3 concentrations under different climate scenarios. AQBAT is an Excel-based “*computer simulation application designed to estimate the human health and welfare benefits, or damages associated with*

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[9] Berry, P. and Schnitter, R. (Eds.), 2022: Health of Canadians in a Changing Climate: Advancing our Knowledge for Action. Ottawa, ON: Government of Canada.

[10] For further details see: Egyed, M., Blagden, P., Plummer, D., Makar, P., Matz, C., Flannigan, M., MacNeill, M., Lavigne, E., Ling, B., Lopez, D. V., Edwards, B., Pavlovic, R., Racine, J., Raymond, P., Rittmaster, R., Wilson, A., and Xi, G., 2022, Air Quality. In P. Berry & R. Schnitter (Eds.), Health of Canadians in a Changing Climate: Advancing our Knowledge for Action. Ottawa, ON: Government of Canada.

changes in Canada's ambient air quality"[11]. Ozone is one of the air pollutants modelled by AQBAT. The impact of climate change was simulated by comparing projected baseline (no climate change) incidence rates for a range of morbidity and mortality health outcomes (shown in Table 1) due to exposure to O_3 with incidence rates corresponding to the temperature-induced changes in O_3 concentrations under the Representative Concentration Pathway (RCP) 4.5 and RCP 8.5[12]. To these ends, AQBAT was 'shocked' by introducing projected increases in daily maximum 1-hour O_3 concentrations in parts per billion volume (ppb-v) in response to projected increases in maximum daily (summer) temperatures. Based on a review of the literature, it was estimated that each degree Celsius increase in maximum daily (summer) temperatures resulted in a 2.9 ppb-v increase in daily maximum 1-hour O_3 concentrations. The estimated incidence rates for the various health outcomes, with and without climate change, were subsequently applied to projections of the applicable populations to estimate acute and chronic excess deaths, acute respiratory symptom days (ARSDs), asthma symptom days (ASDs) and emergency room visits (ERVs).

Table 1: Health outcomes related to O_3 exposures captured by Boyd et al. (2020).

Health outcome	Applicable population
Mortality - acute exposure	100% of the population (all ages)
Mortality - chronic exposure	100% of the population aged 25 years and older
Acute respiratory symptom days (ARSDs)	100% of adults (aged 20 years and older) and 85.7% (non-asthmatic) children aged 5-19
Asthma symptom days (ASDs)	14.3% of (asthmatic) children aged 5-19
Emergency room visits (ERVs)	100% of the population (all ages)

Note: Health outcomes describe the clinical symptoms (consequences) of disease or illness for an affected individual, group or population.

Consistent with other costing studies of climate-related health impacts, estimated physical health outcomes were converted to economic costs by multiplying the projected health outcome by an appropriate projected "unit value":

Economic cost in future year *t* = projected health outcome (physical units) in year *t* x projected "unit value" ($ per physical unit) of the health outcome in year *t*

For the purpose of monetization, morbidity health outcomes are treated separately from mortality outcomes. In short, the valuation of morbidity outcomes is based on the willingness-to-pay (WTP) of individuals to avoid ill-health, which comprises three components:[13]

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[11] Judek, S., et al., 2019: Air Quality Benefits Assessment Tool (AQBAT) User Guide Version 3, 2019.

[12] Projected changes in maximum daily (summer) temperatures were based on outputs from seven GCMs (CCSM4, GFLD-CM3, GFLD-ESM2M, HadGEM2-AO, HadGEM2-ES, MIROC-ESM-CHEM, and MRI-CGCM3), selected to best represent the combined uncertainty across a multi-model ensemble of 25 GCMs (see Boyd et al., 2020 for further details).

[13] PHAC, 2018: Economic Burden of Illness in Canada, 2010. Public Health Agency of Canada (PHAC, Health Economics Team, Ottawa, ON., p. 58.

- Resource costs, which arise from the consumption of medical (primary and secondary care expenditures, drug purchases and formal home care costs) and non-medical resources (e.g., payments for transportation to access health care);
- Opportunity) costs, which arise from foregone leisure opportunities or lost production (from absenteeism or presenteeism) due to ill-health, premature mortality or informal caregiving; and,
- Disutility (human or quality of life) costs, which refers to the value individuals attribute to the emotional distress, pain, and suffering that they, family and friends experience as a result of ill-health or loss of life. These costs represent the intangible component of WTP and are often referred to as welfare losses.

Estimated mortality outcomes were valued using the Value of a Statistical Life (VSL)—a measure of individuals' aggregate WTP to avoid the risk of one death in the population[14]. See Boyd et al. (2020) for further details of the valuation of projected morbidity and mortality health outcomes—including the monetization of heat-related and Lyme disease impacts presented below.

4.1.2 Results: Mortality

Projected welfare losses due to excess mortality from *acute* exposures of Prairie residents to rising O_3 concentrations attributable to climate change are shown in Table 2 for RCP 8.5. By mid-century, estimated welfare losses are approximately $6.9B annually, on average, rising to $17.4B annually by the end of the century. Reflecting the relative populations of each province, the majority of anticipated welfare losses occur in Alberta. Table 3 provides central case estimates for those Census Divisions containing the two main population centres in each province, rounded to the nearest $5M.

Table 2: Projected direct *annual* economic impacts from excess acute mortality arising from population exposures to increased ground-level ozone attributable to climate change (daily max summer temperature) under RCP 8.5 ($ 2020 B)

Province	2050s			2080s		
	Central	Range		Central	Range	
Alberta	3.8	0.1	14.2	10.0	0.2	38.3
Manitoba	1.6	>0.0	6.1	3.6	0.1	14.3
Saskatchewan	1.5	>0.0	5.1	3.8	0.1	12.7
Total	**6.9**	**0.1**	**25.4**	**17.4**	**0.4**	**65.3**

Source: Data from Boyd et al. (2020), where results for RCP 4.5 can be found.

Note: The sum of individual rows may not equal the column total due to rounding. ">0.0" indicates less than $0.05B. The **range** denotes the absolute lower (left) and upper (right) bound estimates. The lower bound estimate is generated by combining the lower confidence interval across all model inputs (i.e., the climate projections, the population and health status projections, the exposure-response functions, and the projected economic unit values). In contrast, the upper bound estimate is generated by combining the upper confidence interval across all model inputs.

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[14] An individual's VSL reflects their marginal rate of substitution between small changes in their own mortality risk and own spending on non-health goods and services in a defined time period; it is not the value an individual, government, or society places on life. For example, if an individual is willing-to-pay (WTP) $900 for a 1/10,000 annual change in the risk of death, then their VSL is equal to $9 million (i.e., $900 ÷ 1/10,000). Similarly, over a population of 10,000, if the average WTP for a 1/10,000 annual reduction in the risk of death is $900, then the number of statistical deaths avoided in the population is one (i.e., 10,000 x 1/10,000) and the VSL is $9 million (i.e., $900 x 10,000).

Table 3: Projected direct *annual* economic impacts from excess acute mortality arising from population exposures in select Census Divisions to increased ground-level ozone attributable to climate change (daily max summer temperature) under RCP 8.5 ($ 2020 M)

Census Division [main population centre]	2050s	2080s
	Central	Central
Division 6 [Calgary]	1,170	3,150
Division 11 [Edmonton]	1,300	3,520
Division 7 [Brandon]	75	180
Division 11 [Winnipeg]	790	1,910
Division 6 [Regina]	315	805
Division 11 [Saskatoon]	330	875

Source: Data from Boyd et al. (2020)

The results for *chronic* exposures of Prairie residents to rising O_3 concentrations attributable to climate change under RCP 8.5 are shown in Table 4. Estimated welfare losses by the 2050s and 2080s are, respectively, approximately $3.3B and $9.2B, on average, annually. Estimated welfare losses for the two most populous Census Divisions in each province are provided in Table 5, rounded to the nearest $5M.

Table 4: Projected direct *annual* economic impacts from excess chronic mortality arising from population exposures to increased ground-level ozone attributable to climate change (daily max summer temperature) under RCP 8.5 ($ 2020 B)

Province	2050s			2080s		
	Central	Range		Central	Range	
Alberta	2.0	>0.0	9.4	5.7	0.1	29.7
Manitoba	0.7	>0.0	3.2	1.6	>0.0	8.4
Saskatchewan	0.7	>0.0	3.0	1.9	>0.0	8.7
Total	**3.3**	**>0.0**	**15.7**	**9.2**	**0.1**	**46.8**

Source: Data from Boyd et al. (2020), where results for RCP 4.5 can be found.

Note: The sum of individual rows may not equal the column total due to rounding. ">0.0" indicates less than $0.05B. The **range** denotes the absolute lower (left) and upper (right) bound estimates. The lower bound estimate is generated by combining the lower confidence interval across all model inputs (i.e., the climate projections, the population and health status projections, the exposure-response functions, and the projected economic unit values). In contrast, the upper bound estimate is generated by combining the upper confidence interval across all model inputs.

Table 5: Projected direct *annual* economic impacts from excess chronic mortality arising from population exposures in select Census Divisions to increased ground-level ozone attributable to climate change (daily max summer temperature) under RCP 8.5 ($ 2020 M)

Census Division [main population centre]	2050s	2080s
	Central	Central
Division 6 [Calgary]	615	1,795
Division 11 [Edmonton]	700	2,060
Division 7 [Brandon]	35	610
Division 11 [Winnipeg]	320	815
Division 6 [Regina]	145	420
Division 11 [Saskatoon]	125	375

Source: Data from Boyd et al. (2020)

4.1.3 Results: Morbidity

Projected welfare losses due to excess morbidity outcomes—acute respiratory symptom days (ARSDs), asthma symptom days (ASDs) and emergency room visits (ERVs)—from exposures of Prairie residents to rising O_3 concentrations attributable to climate change are shown in Table 6 for RCP 8.5. By mid-century, estimated welfare losses are approximately $64M annually, on average, rising to $180M annually by the end of the century. As expected, the majority of anticipated welfare losses occur in Alberta due to its larger projected population over the course of the century. Of the estimated total welfare losses across the Prairies in both the 2050s and 2080s, roughly 75% are due to ARSDs; ASDs and ERVs account for about 17% and 8%, respectively.

Table 6: Projected direct *annual* economic impacts from excess morbidity health outcomes arising from population exposures to increased ground-level ozone attributable to climate change (daily max summer temperature) under RCP 8.5 ($ 2020 M)

Province	2050s			2080s		
	Central	Range		Central	Range	
Alberta	40	>0	414	118	>0	1,350
Manitoba	13	>0	135	32	>0	383
Saskatchewan	11	>0	108	30	>0	333
Total	64	>0	656	180	>0	2,066

Source: Data from Boyd et al. (2020), where results for RCP 4.5 can be found.

Note: The sum of individual rows may not equal the column total due to rounding. ">0" indicates less than $0.5M. The **range** denotes the absolute lower (left) and upper (right) bound estimates. The lower bound estimate is generated by combining the lower confidence interval across all model inputs (i.e., the climate projections, the population and health status projections, the exposure-response functions, and the projected economic unit values). In contrast, the upper bound estimate is generated by combining the upper confidence interval across all model inputs.

4.2 Air quality—wildfire smoke

Wildfire smoke contains many air pollutants of concern—e.g., particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x)—that epidemiological studies have linked with mortality and morbidity outcomes. Smoke related $PM_{2.5}$ (i.e., fine particulates less than 2.5 microns in width) levels are most closely associated with adverse health outcomes as they can be deeply inhaled into the lungs[15].

No studies have assessed the future economic consequences of wildfire smoke for public health in Canada. However, Matz et al. (2020) conducted a multi-year retrospective assessment of the economic burden of wildfire smoke in Canada for the years 2013-2015 and 2017-2018[16]. With climate change anticipated to increase the area burned and amount of fuel burned in all forests in Canada by 2100[17], the results for the Prairies from Matz et al. (2020) are presented below.

The per cent of Prairie landmass and population affected with wildfire-$PM_{2.5}$ above specific concentrations are provided in Table 7 and Table 8, respectively. Over 2013 to 2018, about 85%, 71% and 88% of the landmass of Alberta, Manitoba and Saskatchewan had average wildfire-$PM_{2.5}$ concentrations of 1 μg/m^3 or more, affecting about 81%, 48% and 81% of the population.

Table 7: Per cent of Prairie landmass with average May-September wildfire-$PM_{2.5}$ concentrations above threshold concentrations 2013-2015, 2017-2018

	0.2 μg/m^3	1.0 μg/m^3	5.0 μg/m^3	10.0 μg/m^3
2013				
Alberta	100.0	42.0	0.2	0.0
Manitoba	100.0	72.4	4.4	0.6
Saskatchewan	100.0	50.5	4.5	0.7
2014				
Alberta	100.0	100.0	4.7	0.1
Manitoba	100.0	79.2	0.0	0.0
Saskatchewan	100.0	100.0	2.3	0.0
2015				
Alberta	100.0	92.8	3.4	0.0
Manitoba	100.0	75.2	0.0	0.0
Saskatchewan	100.0	100.0	17.5	2.3
2017				
Alberta	100.0	93.1	16.8	1.0
Manitoba	100.0	97.1	1.1	0.1
Saskatchewan	100.0	100.0	2.6	0.8
2018				
Alberta	100.0	98.2	21.7	0.0
Manitoba	99.1	33.4	0.1	0.0
Saskatchewan	100.0	89.0	0.1	0.0

Source: Matz et al. (2020), supplementary materials

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[15] Wildfire Smoke and Your Health, BC Centre for Disease Control, May 2021.

[16] Matz., C., Egyed, M., Xi, G., Racine, J., Pavlovic, R., Rittmaster, R., Henderson, S. and Stieb, D., 2020, Health impact analysis of PM2.5 from wildfire smoke in Canada (2013-2015, 2017-2018), The Science of the Total Environment, 725, 138506.

[17] Gosselin, P., Campagna, C., Demers-Bouffard, D., Qutob, S., and Flannigan, M., 2022: Natural Hazards. In Berry, P. and Schnitter, R. (Eds.), Health of Canadians in a Changing Climate: Advancing our Knowledge for Action. Ottawa, ON: Government of Canada.

Table 8: Per cent of Prairie population with average May-September wildfire-PM$_{2.5}$ concentrations above threshold concentrations 2013-2015, 2017-2018

	0.2 µg/m^3	1.0 µg/m^3	5.0 µg/m^3	10.0 µg/m^3
2013				
Alberta	100.0	9.4	0.0	0.0
Manitoba	100.0	6.7	0.1	0.0
Saskatchewan	100.0	6.0	0.1	0.1
2014				
Alberta	100.0	1000	0.0	0.0
Manitoba	100.0	12.1	0.0	0.0
Saskatchewan	100.0	100.0	0.1	0.0
2015				
Alberta	100.0	97.4	19.0	0.0
Manitoba	100.0	99.8	0.0	0.0
Saskatchewan	100.0	100.0	2.4	0.3
2017				
Alberta	100.0	99.9	38.7	0.4
Manitoba	100.0	100.0	0.4	0.0
Saskatchewan	100.0	100.0	0.6	0.2
2018				
Alberta	100.0	100.0	39.4	0.0
Manitoba	100.0	23.5	0.1	0.0
Saskatchewan	100.0	99.6	0.0	0.0

Source: Matz et al. (2020), supplementary materials

Matz et al. (2020) used Health Canada's AQBAT 3.0 to quantify and monetize the health impacts attributable to the wildfire-PM$_{2.5}$ concentrations and population exposures listed in Table 7 and Table 8. The mortality results, including economic valuation, are presented in Table 9. Estimated morbidity outcomes were only available for Canada. Over the five years assessed by Matz et al. (2020), estimated welfare losses on the Prairies ranged from $105M to $395M for acute health mortality impacts and $1,035M to $4,155M for chronic health mortality impacts. The lowest and highest losses were incurred in 2013 and 2017, respectively, reflecting the relatively low and high per cent of the Prairie population exposed to the specified concentrations of wildfire-PM$_{2.5}$ in those years. The largest welfare losses were experienced in Alberta—largely due to its higher population vis-à-vis Manitoba and Saskatchewan, but also because of the relatively high levels of population exposure to wildfire-PM$_{2.5}$, particularly in 2017 and 2018 (as evident from the mortality rates in those years).

Table 9: Acute and chronic mortality impacts and economic consequences attributable to wildfire-PM$_{2.5}$ exposures for 2013-2015, 2017-2018

	Acute mortality			Chronic mortality		
	Premature deaths	Mortality rate	$ 2020 M	Premature deaths	Mortality rate	$ 2020 M
2013						
Alberta	7	0.18	55	71	1.78	540
Manitoba	3	0.24	25	35	2.77	265
Saskatchewan	3	0.27	25	30	2.73	230
2014						
Alberta	19	0.47	145	200	4.90	1,520
Manitoba	4	0.31	30	37	2.89	280
Saskatchewan	6	0.54	45	60	5.39	455
2015						
Alberta	28	0.68	215	290	7.00	2,205
Manitoba	7	0.54	55	74	5.73	560
Saskatchewan	9	0.80	70	96	8.56	730
2017						
Alberta	42	0.99	320	440	10.37	3,345
Manitoba	4	0.30	30	45	3.37	340
Saskatchewan	6	0.52	45	62	5.39	470
2018						
Alberta	42	0.98	320	430	10.00	3,270
Manitoba	4	0.30	30	40	2.96	305
Saskatchewan	5	0.43	40	53	4.56	405

Source: Mortality data from Matz et al. (2020), supplementary materials; premature deaths valued using a VSL of $7.6M (as per Matz et al., 2020) rounded to the nearest $5M.

Notes: Mortality rate is the number of excess deaths per 100,000 population

4.3 High temperatures

Evidence of an association between ambient temperature and mortality or morbidity outcomes has been documented in many studies[18]. Those particularly at risk include older adults, pregnant women, children, people with chronic health conditions, and populations with increased social vulnerability with less access to information, resources, healthcare, and other means to prepare for and avoid the health risks of high temperatures.

4.3.1 Approach

To quantify mortality impacts attributable to high temperatures under projected climate change scenarios Boyd et al (2020) used exposure-response functions obtained from Gasparrini et al. (2015)[19], who estimated excess deaths attributable to heat exposures for 384 cities globally, including 21 Canadian cities. Excess deaths were defined as the fraction of daily (all-cause) mortality attributable to mean daily temperatures above the "optimum temperature" for each city (i.e., the mean daily temperature between the 2.5th and 97.5th percentiles that corresponded to the minimum daily mortality rate). For example, it

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[18] Gosselin et al., 2022, ibid.

[19] Gasparrini, A., et al., 2015: Mortality risk attributable to high and low ambient temperature: a multi-country observational study. Lancet, 386, 369-375.

was estimated that 0.46% of daily (all-cause) mortality in Edmonton was attributed to mean daily temperatures above the optimum—minimum mortality—temperature of 17.5°C. Similarly, for Saskatoon and Winnipeg it was estimated that 0.53% and 0.54% of daily (all-cause) mortality, respectively, was attributed to mean daily temperatures above 16.1°C and 17.2°C.

Box 1: Why were exposures to extreme cold not included in the analysis?

Although there is robust evidence that hot weather is associated with short-term increases in mortality and morbidities, the extent to which observed excess mortality in winter months[20] is directly attributable to cold weather exposures remains unclear and is currently being debated in the literature.[21] For instance, in a study of 26 U.S. and 3 French cities, Kinney et al. (2012) concluded that excess winter mortality is not largely driven by cold temperature, but rather is driven by other seasonal factors, such as influenza. Based on an extensive literature review considering the role of temperature in the etiology of specific cold-related health outcomes and in mortality patterns during winter months, Ebi and Mills (2013) concluded that the association between temperature and higher rates of mortality in the winter is relatively weak. Additionally, the impact of cold spells on mortality has been found to be negligible (Barnett et al., 2012); cold spells are also only a marginal contributor to excess winter deaths (Ebi and Mills, 2013). In light of the conclusions of this literature, Boyd et al. (2020) omitted consideration of the impact of climate change on cold-related mortality and morbidity.

Regarding morbidities, Bai et al. (2016 and 2017)[22] investigated the relationship between ambient air temperatures and hospitalizations for a range of heat-related diseases and conditions in Ontario between 1996 and 2013. The approach used is like that used by Gasparrini et al. (2015). Excess hospitalizations were defined as admissions attributable to mean daily temperatures above the “optimum temperature” (i.e., the mean daily temperature between the 2.5th and 97.5th percentiles that corresponded to the minimum daily hospitalization rate). The most robust models were estimated for coronary heart disease (CHD), stroke, hypertensive diseases, and diabetes. Boyd et al. (2020) used the exposure-response functions from Bai et al. (2016 and 2017) to assess the impact of climate change on hospitalizations for these four diseases.

The economic valuation of projected excess mortality and hospitalizations attributable to climate change was described above in Section 4.1.1; further detailed can be found in Boyd et al. (2020). In contrast to the valuation of air quality impacts on public health, projected excess hospitalizations from heat exposures only include direct resource and opportunity costs; they do not include the valuation of disutility impacts. Thus, the morbidity results presented below provide a measure of financial loss as opposed to a true measure of WTP to avoid hospitalization.

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[20] See, for example, Analitis, A., et al., 2008: Effects of cold weather on mortality: results from 15 European cities within the PHEWE Project. American Journal of Epidemiology, 168 (12), 1397-408.

[21] Kinney, P., et al., 2012: Winter mortality in a changing climate: will it go down? Bulletin épidémiologique hebdomadaire (BEH), 148–151; Barnett, A., et al., 2012: Cold and heat waves in the United States. Environment Research, 112, 218-224; Ebi, K. and Mills, D., 2013: Winter mortality in a warming climate: a reassessment. WIREs Climate Change, 4, 203–212; and Staddon, P., et al., 2014: Climate warming will not decrease winter mortality. Nature Climate Change, 4, 190–194.

[22] Bai, L., et al., 2016: Hospitalizations from hypertensive disease, diabetes, and arrhythmia in relation to low and high temperatures: population-based study. Nature Scientific Reports, 6, 30283, DOI:10.1038/srep30283; and Bai, L., et al., 2017: Increased coronary heart disease and stroke hospitalizations from ambient air temperatures in Ontario. Heart, 104, 673-679.

4.3.2 Results: Mortality

Projected welfare losses due to excess mortality from exposures of Prairie residents to rising temperatures attributable to climate change are shown in Table 10 for RCP 8.5. By mid-century, estimated welfare losses are approximately $0.6B annually, on average, rising to $1.4B annually by the end of the century. Reflecting the relative populations of each province, most of the anticipated welfare losses occur in Alberta. However, when normalizing for the projected population in each province, the largest annual losses per 100,000 population occur in Manitoba (e.g., $8.6M per 100,000 by the 2050s) followed closely Saskatchewan (e.g., $8.2M per 100,000 by the 2050s). A higher proportion of the population in these provinces will experience relatively larger increases in degree days above the minimum mortality thresholds than in Alberta. Table 11 provides central case estimates for those Census Divisions containing the two main population centres in each province, rounded to the nearest $5M.

Table 10: Projected direct *annual* economic impacts from excess mortality arising from population exposures to heat attributable to climate change under RCP 8.5 ($ 2020 M)

Province	2050s			2080s		
	Central	Range		Central	Range	
Alberta	295 [4.5]	105	580	745 [7.8]	255	1,565
Manitoba	155 [8.6]	55	305	340 [14.9]	110	735
Saskatchewan	135 [8.2]	50	270	335 [14.6]	105	700
Total	**585 [5.8]**	**205**	**1,155**	**1,420 [10.1]**	**475**	**3,000**

Source: Data from Boyd et al. (2020), where results for RCP 4.5 can be found.

Note: The sum of individual rows may not equal the column total due to rounding. For the central estimate, the figure in the brackets represents the welfare loss per projected 100,000 population (in $ 2020 M). The **range** denotes the absolute lower (left) and upper (right) bound estimates. The lower bound estimate is generated by combining the lower confidence interval across all model inputs (i.e., the climate projections, the population and health status projections, the exposure-response functions, and the projected economic unit values). In contrast, the upper bound estimate is generated by combining the upper confidence interval across all model inputs.

Table 11: Projected direct *annual* economic impacts from excess mortality arising from population exposures in select Census Divisions to heat attributable to climate change under RCP 8.5 ($ 2020 M)

Census Division [main population centre]	2050s	2080s
	Central	Central
Division 6 [Calgary]	120	260
Division 11 [Edmonton]	105	235
Division 7 [Brandon]	10	15
Division 11 [Winnipeg]	80	150
Division 6 [Regina]	30	65
Division 11 [Saskatoon]	40	85

Source: Data from Boyd et al. (2020)

4.3.3 Results: Morbidity

Projected costs due to excess morbidity outcomes—hospital admissions due to coronary heart disease, stroke, hypertensive diseases, and diabetes—from exposures of Prairie residents to rising temperatures attributable to climate change are shown in Table 12 for RCP 8.5. By mid-century, estimated financial losses are approximately $30M annually, on average, rising to about $80M annually by the end of the century. The majority of anticipated welfare losses occur in Alberta due to its larger projected population over the course of the century. However, normalizing for the projected population of each province in the 2050s and 2080s, relative differences in financial losses are much less pronounced, with losses in Alberta and Saskatchewan per 100,000 population being very similar (see Figure 3).

Over both periods, resource costs account for 94%-95% of total costs, with opportunity costs accounting for only 5%-6% of the totals.

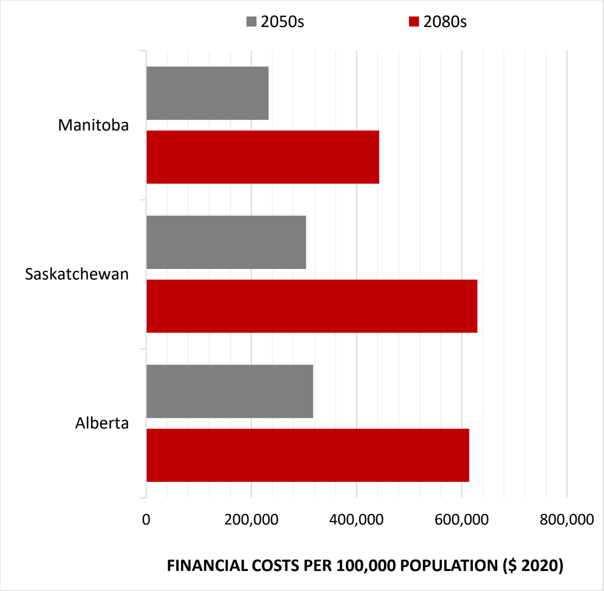
Table 12: Projected direct *annual* economic impacts from excess heat-related hospitalizations arising from population exposures to rising temperatures attributable to climate change under RCP 8.5 ($ 2020 M)

Province	2050s			2080s		
	Central	Range		Central	Range	
Alberta	20	8	34	56	20	101
Manitoba	4	2	8	11	4	21
Saskatchewan	5	2	8	14	5	25
Total	**30**	**11**	**50**	**82**	**28**	**147**

Source: Data from Boyd et al. (2020), where results for RCP 4.5 can be found.

Note: The sum of individual rows may not equal the column total due to rounding. The **range** denotes the absolute lower (left) and upper (right) bound estimates. The lower bound estimate is generated by combining the lower confidence interval across all model inputs (i.e., the climate projections, the population and health status projections, the exposure-response functions, and the projected economic unit values). In contrast, the upper bound estimate is generated by combining the upper confidence interval across all model inputs.

Figure 3: Projected direct *annual* economic impacts from excess heat-related hospitalizations arising from population exposures to daily mean temperatures attributable to climate change under RCP 8.5



4.4 Lyme disease

Climate change is anticipated to modify the geographic range, seasonal distribution, and abundance of diseases transmitted by arthropod vectors, exposing more people in Canada to ticks that carry Lyme disease or other pathogens, and to mosquitoes that transmit West Nile and dengue[23].

4.4.1 Approach

Boyd et al. (2020) estimated new incidence cases (per 100,000 population) of Lyme disease in Canada as a function of changes in mean annual temperature under different future climate scenarios (RCP 4.5 and 8.5) and socioeconomic scenarios. The relationship between mean annual temperature and the incidence of Lyme disease in an exposed population was modelled using point estimates from an exposure-response function generated by Dumic and Severnini (2018). Using annual data for 468 counties in 15 North-Eastern and Mid-Western states for the period 2000 to 2016, Dumic and Severnini (2018) estimated a statistically significant relationship between annual Lyme disease incidence rates and annual average temperatures across seven temperature increments (below 5°C, 5–7°C, 7–9°C, 9–11°C, 11–13°C, 13–15°C, and above 15°C). The estimated function—used by Boyd et al. (2020)—is shown in Figure 4.

The extent of the exposed population included in the assessment of Lyme disease in Canada was limited to provinces with established tick populations—Manitoba, Ontario, Quebec and the Atlantic provinces,

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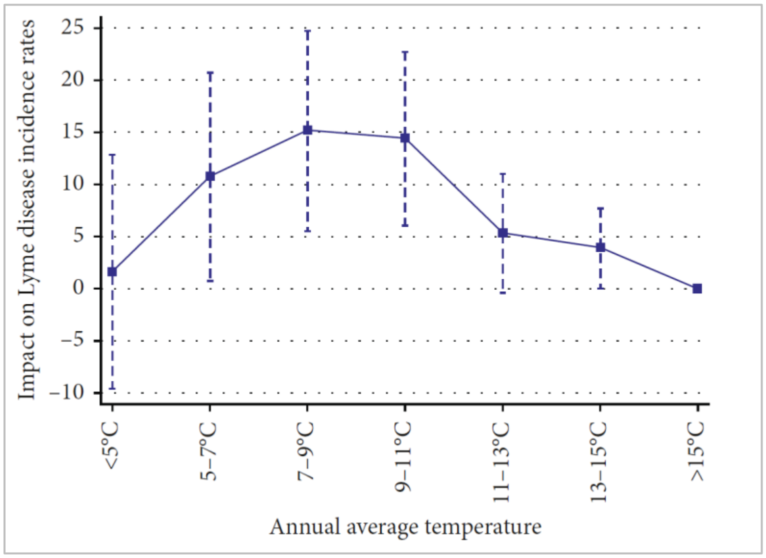
[23] Ogden, N., Bouchard, C., Brankston, G., Brown, E., Corrin, T., Dibernardo, A., Drebot, M., Fisman, D., Galanis, E., Greer, A., Jenkins, E., Kus, J., Leighton, P., Lindsay, L., Lowe, A.-M., Ludwig, A., Morris, S., Ng, V., Vrbova, L., Waddell, L. and Wood, H., 2022, Infectious Diseases. In P. Berry & R. Schnitter (Eds.) ibid.

and excluded populations at elevations greater than 500m above sea-level (see Boyd et al., 2020 for an explanation). Consequently, no results are available for Alberta and Saskatchewan.

Figure 4: Exposure-response function for the incidence of Lyme disease (cases per 100,000 population)



Source: Boyd et al. (2020), reproduced from Dumic and Severnini (2018)

Notes: Point estimates are blue squares, with vertical dashed lines representing the 95% (lower and upper) confidence interval. The zero value at >15°C does not imply that Lyme disease incidence is 0; >15°C is the reference or benchmark temperature used by Dumic and Severnini for the statistical analysis.

The valuation of projected new incident cases of Lyme disease is more complex than for projected morbidity and mortality outcomes attributable to heat and ground-level ozone exposures, since each infection can give rise to a range of clinical manifestations—from erythema migrans (an enlarging skin lesion at the site of the tick bite) to disseminated Lyme borreliosis (which may manifest as a multi-symptom disease with skin, cardiac, musculoskeletal, and neurological symptoms), and in rare cases, to a range of chronic symptoms (such as fatigue, pain and cognitive impairment). WTP-based economic unit values were generated for new incident cases of Lyme disease that captured the range of potential clinical outcomes (see Boyd et al., 2020 for further details).

4.4.2 Results

Projected welfare losses due to new incident cases of Lyme disease in Manitoba attributable to climate change are shown in Table 13 for RCP 8.5. By mid-century, estimated welfare losses are approximately $440M annually, on average, rising to about $645M annually by the end of the century. Roughly 1.1%-1.3% of the estimated losses are resource costs (e.g., expenditures on health care services), 2.2%-2.4% are opportunity costs (i.e., lost economic output), with the remaining 96%-97% disutility costs. Reflecting the relative populations of each Census Division, the Divisions containing Winnipeg (11) and Brandon (07) incur the largest anticipated welfare losses in both periods.

Table 13: Projected direct *annual* economic impacts from new incident cases of Lyme disease in Manitoba attributable to climate change under RCP 8.5

Census Division	2050s		2080s	
	New cases	$ 2020 M	New cases	$ 2020 M
Division 01	220	7	340	11
Division 02	970	29	1,290	40
Division 03	750	22	900	28
Division 04	120	4	170	5
Division 05	170	5	230	7
Division 06	130	4	180	6
Division 07	830	25	1,200	37
Division 08	170	5	240	7
Division 09	320	10	420	13
Division 10	150	4	200	6
Division 11	8,990	269	12,090	374
Division 12	290	9	420	13
Division 13	590	18	880	27
Division 14	220	7	330	10
Division 17	210	6	390	12
Division 18	240	7	430	13
Division 19	110	3	280	9
Division 20	60	2	150	5
Division 21	100	3	320	10
Division 22	90	3	440	14
Division 23	10	>1	30	1
Manitoba	**14,730**	**440**	**20,940**	**645**

Source: Data from Boyd et al. (2020)

Note: The sum of individual rows may not equal the column total due to rounding.

5 WORKFORCE

Notwithstanding the significance of the health risks for the general public, climate change may present an even greater risk to the health and safety of the workforce. Employees are often exposed to the effects of climate change for longer durations and at greater intensities than the public. In part, because workers are less able to avoid exposure to adverse conditions than are the public, who can choose to stay indoors, in air-conditioned environments. And just as the health of some population groups are more affected by climate change than others—because of factors like where they live, their age, existing health status etc.—certain groups of workers are more vulnerable to climate-related impacts because of where they work, the type of work they do, or both.

In general, climate change can directly impact workers in two main ways:

1. By altering the severity or frequency of known climate-related workplace hazards experienced today, such as storms, high temperatures and heatwaves, wildfires, and air pollution. These hazards are likely already contributing to occupational injuries, illnesses and fatalities, reduced productivity, and will only be made worse by climate change.
2. By creating unprecedented or unanticipated occupational hazards, such as widening the ranges of infectious disease vectors like ticks and mosquitos.

In this section, projected direct economic impacts resulting from the exposure of workers on the Prairies to increasingly higher temperatures due to climate change are presented. The economic impacts of other climate-related impact pathways for workers on the Prairies have not yet been quantified.

5.1 Labour productivity and high temperatures

An emerging field of research on the macroeconomic consequences of climate change examines the impact of temperature and heat stress on the productivity of workers across different economic sectors.[24] There is an observable relationship between workplace temperatures and worker performance; beyond a certain temperature the hourly productivity of workers declines.[25] When an employee performs strenuous physical work, heat is generated by the body. The risk of overheating increases with the level of physical exertion required to perform a given task, the duration of the task, the experience of the worker in performing the task (i.e., their level of acclimatization), and the ambient temperature of the work

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[24] For a review see: Dell, M., Jones, D. and Olken, B., 2014: What do we learn from the weather? The new climate-economy literature. Journal of Economic Literature, 52 (3), 740-798; Heal, G. and Park, J., 2016: Temperature stress and the direct impact of climate change: a review of an emerging literature. Review of Environmental Economics and Policy, 10 (2), 1-17; Kjellstrom, T., et al., 2015: Heat impacts on work, human performance and daily life. In: Climate Change and Public Health [Levy, B. and Patz, J., (eds.)], Oxford University Press, New York, 73–86; or Newell, R., Prest, B. and Sexton, S., 2018: The GDP-temperature relationship: implications for climate change damages. RFF WP 18-17, Resources for the Future, Washington, DC, 61 pp.

[25] Dasgupta, S., et al. (2021). Effects of climate change on combined labour productivity and supply: an empirical, multi-model study. Lancet Planet Health, 5, 455-465; Zivin, J. and Neidell, M. (2014). Temperature and the allocation of time: implications for climate change. Journal of Labour Economics, 32, 1–26; and Dunne, J., Stouffer, R. and John, J. (2013). Reductions in labour capacity from heat stress under climate warming. Nature Climate Change, 3, 563–566.

environment.[26] Heat generated needs to be transferred to the external environment to avoid increases in the body's temperature. If the body is unable to dissipate the heat—perhaps because of prolonged exposure, or water or salt deficiencies—it begins to cause dizziness, muscle cramps, and fever. In the extreme, prolonged exposure to high temperatures can cause acute cardiovascular, respiratory, and cerebrovascular distress, which can require hospitalization or be life threatening.

At lower temperatures in the workplace, before these serious health effects occur, workers can experience diminished 'work ability'. Temperature stress may affect workers in two ways:

1. It may cause direct physical or psychological discomfort.
2. It may reduce task productivity, altering the increment of effort exerted within any given hour or the marginal return of that effort.

In turn, these two direct effects may adversely affect labour supply (hours) and/or labour productivity (output per hour worked).[27]

Below, the approach used by Boyd et al. (2020)[28] to estimate the economic impact of climate change on the productivity of workers on the Prairies (and other Provinces and Territories) is briefly described before key results are presented.

5.2 Approach

Using a panel data set created from the American Time-Use Survey, Graff Zivin and Neidell (2014) examined the response of labour to daily maximum temperature across 5°F (roughly 2.8°C) increments, from >25°F (-3.9°C) to 105°F (40.6°C). They found that days with extreme temperatures were associated with significant changes in the time allocated to labour by individuals. On days when maximum temperatures exceeded 37.8°C (100°F), for example, workers in industries with relatively high exposure to weather[29] reduced time allocated to labour by nearly one hour compared to inflection temperatures in the 24.4-26.7°C range, which represents a 14% reduction in labour supply for the day. However, they found no statistically significant temperature-labour supply effects in other industries that are less exposed to weather (e.g., non-manufacturing, largely indoor occupations). Boyd et al. (2020) used Graff Zivin and Neidell's estimates of the response of labour supply to daily maximum temperatures (see Figure 5) to calculate incremental labour impacts and associated economic consequences for "high risk" industries in Canada under future climate (RCP 4.5 and RCP 8.5) and socioeconomic (growth) scenarios. As per Graff Zivin and Neidell (2014), "high risk" industries are: (North American Industrial Classification

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[26] ESDC (2018). Thermal stress in the workplace: Guideline 2018. Employment and Social Development Canada, Ottawa (available at https://www.canada.ca/en/employment-social-development/services/health-safety/reports/thermal-stress-work-place.html).

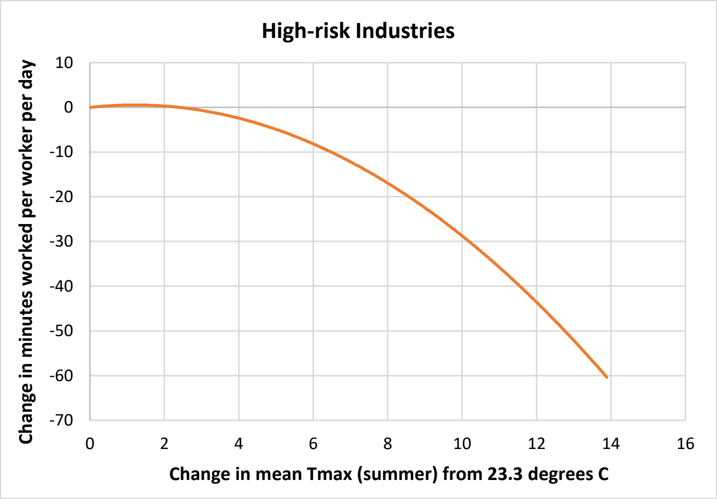
[27] See, for example, ILO (2019). Working on a warmer planet: the impact of heat stress on labour productivity and decent work. International Labour Organization (ILO), Geneva, Switzerland, or Kjellstrom, T., et al. (2016). Heat, human performance, and occupational health: a key issue for the assessment of global climate change impacts. Annual Review of Public Health, 37, 97–112.

[28] Boyd, R., Eyzaguirre, J., Poulsen, F., Siegle, M., Thompson, A., Yamamoto, S., Osornio-Vargas, Erickson, A. and Urcelay, A., 2020: Costing Climate Change Impacts on Human Health Across Canada. Technical report prepared by ESSA Technologies for the Canadian Institute of Climate Choices.

[29] High-exposure industries are industries where the work is performed primarily outdoors, as well as manufacturing, where facilities are sometimes not climate controlled, and the production processes often generate considerable heat.

System (NAICS) Code 11) Agriculture, Forestry, Fishing, and Hunting; (NAICS 21) Mining, Quarrying, and Oil and Gas Extraction; (NAICS 22) Utilities; (NAICS 23) Construction; (NAICS 31-33) Manufacturing; and (NAICS 48-49) Transportation and Warehousing.

Figure 5: Illustration of exposure-response function for labour supply in "high risk" industries and maximum daily temperature above the inflection temperature of 23.3°C



Source: Derived from Boyd et al. (2020) based on Graff Zivin and Neidell (2014)

The function in Figure 5 was coupled with projections of (a) the workforce in each industry across Canada and (b) changes in maximum daily (summer) temperature under RCP 4.5 and RCP 8.5 (relative to the 1971-2000 baseline period), to estimate changes in labour hours supplied, which are subsequently monetized.

Projections of the future workforce across Canada by 2-digit NAICS Codes were provided by the Canadian Climate Institute.

Estimated direct climate induced changes in labour supply were monetized using two metrics:

1. **Total payroll compensation** (per hour worked). It is calculated as the ratio between total compensation payments and the number of hours worked in all jobs. Total compensation is a measure of the total payroll costs of producers. It consists of all payments, whether cash or in-kind, to workers for services rendered, including salaries and social contributions paid by employers, plus an imputed labour income for self-employed workers.
2. **Labour productivity** (per hour worked). It is calculated as the ratio between value added generated and hours worked in all jobs. Labour productivity provides a measure of losses to society, differentiating it from the loss of compensation—a measure that more reflects losses for the individual worker. For a specific sector, value added is given by that sector's gross output (mainly sales) less purchases of intermediate goods and services supplied by other sectors. It corresponds to GDP at basic prices.

The above monetary metrics were calculated for each “high risk” 2-digit NAICS industry for the 2020 base year using provincial-level data obtained from Statistics Canada. As per US EPA (2015 and 2017)[30], future values for each metric were generated by adjusting the 2020 base year values for projected growth in real GDP per capita.

5.3 Results

By mid-century under RCP 8.5, about 14.4 million hours annually, on average, are estimated to be lost in “high risk” industries on the Prairies, rising to 35.5 million hours annually by the end of the century (see Figure 6). The largest absolute reductions in labour supply occur in Alberta, though this is driven by the overall size of the workforce in the province vis-à-vis Manitoba and Saskatchewan. Normalizing for the relative size of the workforce in each province, the largest reductions in projected labour supply occur in Manitoba (-1.64%), followed by Saskatchewan (-1.55%), then Alberta (-1.29%) (see Figure 7). All else being equal, workers in “high risk” industries in Manitoba are projected to experience relative more additional degree days above the inflection temperature of 23.3°C than in the other Prairie provinces as a result of climate change.

Figure 6 also provides a breakdown of lost labour hours by “high risk” industry for each province. The most adversely impacted industries across the Prairies are “manufacturing” (NAICS 31-33), “construction” (NAICS 23) and “transportation and warehousing” (NAICS 48-49); though differences between sectors are primarily driven by the relative size of the projected workforce, as opposed to the vulnerability of workers in those industries. This is evident from the exposure-response functions for each industry (not shown), which have fairly similar shapes. In Saskatchewan projected losses in “agriculture and forestry” (NACIS 11) rival those in the other most impacted industries.

While NAICS 21 is classed as a “high risk” industry in the literature (in terms of the vulnerability of the workforce to heat exposure), this may not be the case for places like Calgary, where a sizable portion of workers in the industry likely work in offices as opposed to the field. To the extent that all workers in NAICS 21 are office-based, the results presented below will overstate the scale of potential losses over the projection period. At the same time, there will be some degree of labour supply reductions in the other 14 “low risk” 2-digit NAICS industries not included in the analysis conducted by Boyd et al. (2020).

The corresponding annual direct economic impacts of the projected reductions in labour supply are provided in Table 14 (forgone labour income under RCP 4.5), Table 15 (forgone labour income under RCP 8.5), Table 16 (forgone labour productivity under RCP 4.5) and Table 17 (forgone labour productivity under RCP 8.5) by “high risk” industry and province for the 2050s and 2080s. The values in the tables represent the projected changes in labour income and productivity due to exposure of workers in “high-risk” industries to high temperatures *attributable* to climate change under each climate scenario.

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[30] US EPA, 2015: Climate Change in the United States: Benefits of Global Action. U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-15-001. Washington, DC; and US EPA, 2017: Multi-Model Framework for Quantitative Sectoral Impacts Analysis: A Technical Report for the Fourth National Climate Assessment. U.S. Environmental Protection Agency, Office of Atmospheric Programs, EPA 430-R-17-001.

Figure 6: Projected labour hours lost *annually* due to the exposure of workers in "high-risk" industries to high temperatures attributable to climate change under RCP 8.5 (central case)

Source: Data from Boyd et al. (2020)

Across all three Prairie provinces and "high risk" industries, direct **labour income losses** due to projected increases in maximum daily temperature (relative to the 1971-2000 baseline period) are estimated at:

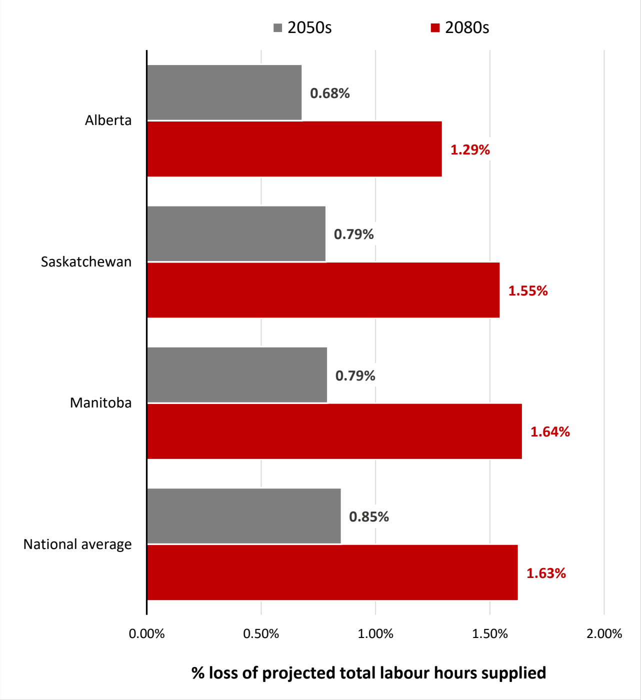
- $0.4 B annually (on average) by the 2050s under RCP 4.5, rising to $0.8 B by the 2080; and
- $0.7 B annually (on average) by the 2050s under RCP 8.5, rising to $1.8 B by the 2080s.

Direct **labour productivity losses** due are estimated at:

- $0.8 B annually (on average) by the 2050s under RCP 4.5, rising to $1.6 B by the 2080; and
- $1.3 B annually (on average) by the 2050s under RCP 8.5, rising to $3.7 B by the 2080s.

The most adversely impacted industries in terms of foregone labour income—irrespective of time period or climate scenario—are manufacturing followed by construction. However, the contribution of the construction industry to total value added losses is reduced, reflecting the relatively higher labour productivity values ($ GDP per hour) of the primary extraction, manufacturing and transportation and warehousing industries on the Prairies.

Figure 7: Projected fraction of total labour hours supplied (no further climate change) lost *annually* due to the exposure of workers in "high-risk" industries to high temperatures attributable to climate change under RCP 8.5 (central case): Prairie provinces versus national average



Source: Data from Boyd et al. (2020)

Table 14: Projected *annual* changes in labour income (compensation) due to exposure of workers in "high-risk" industries to higher temperatures under RCP 4.5 ($ 2020 M)

Alberta	**2050s**			**2080s**		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-6	9	-12	-8	13	-20
Mining, quarrying, oil & gas extraction	-57	90	-122	-91	147	-222
Utilities	-12	18	-24	-24	37	-56
Construction	-63	101	-138	-119	192	-290
Manufacturing	-63	86	-118	-151	228	-344
Transportation & warehousing	-32	48	-65	-63	100	-151
Total	**-232**	**351**	**-480**	**-457**	**717**	**-1,083**

Manitoba	**2050s**			**2080s**		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-4	5	-8	-5	7	-12
Mining, quarrying, oil & gas extraction	-4	5	-8	-8	11	-20
Utilities	-4	6	-9	-6	8	-15
Construction	-25	38	-56	-48	68	-120
Manufacturing	-36	50	-75	-74	100	-178
Transportation & warehousing	-19	27	-40	-37	51	-91
Total	**-92**	**132**	**-197**	**-179**	**246**	**-437**

Saskatchewan	**2050s**			**2080s**		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-6	8	-13	-8	10	-22
Mining, quarrying, oil & gas extraction	-10	14	-23	-13	16	-35
Utilities	-3	4	-7	-5	6	-14
Construction	-17	24	-40	-29	36	-77
Manufacturing	-21	25	-41	-49	57	-122
Transportation & warehousing	-12	15	-24	-23	28	-60
Total	**-70**	**89**	**-148**	**-129**	**153**	**-329**

Source: Data from Boyd et al. (2020)

Note: The **range** denotes the absolute lower (left) and upper (right) bound estimates. The lower bound estimate is generated by combining the lower confidence interval across all model inputs (i.e., the climate projections, the workforce projections, the exposure-response functions, and the projected economic unit values). In contrast, the upper bound estimate is generated by combining the upper confidence interval across all model inputs.

Table 15: Projected *annual* changes in labour income (compensation) due to exposure of workers in "high-risk" industries to higher temperatures under RCP 8.5 ($ 2020 M)

Alberta	**2050s**			**2080s**		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-8	13	-18	-19	30	-50
Mining, quarrying, oil & gas extraction	-87	139	-188	-221	355	-599
Utilities	-18	28	-37	-59	93	-156
Construction	-96	156	-211	-289	465	-785
Manufacturing	-100	137	-186	-372	561	-948
Transportation & warehousing	-49	75	-101	-157	247	-417
Total	**-359**	**548**	**-742**	**-1,116**	**1,751**	**-2,955**

Manitoba	**2050s**			**2080s**		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-5	7	-11	-11	15	-30
Mining, quarrying, oil & gas extraction	-6	8	-12	-19	25	-52
Utilities	-6	8	-13	-13	18	-36
Construction	-35	52	-78	-106	147	-300
Manufacturing	-51	69	-105	-161	217	-443
Transportation & warehousing	-26	37	-56	-81	111	-227
Total	**-128**	**181**	**-276**	**-390**	**532**	**-1,088**

Saskatchewan	**2050s**			**2080s**		
	Central	Range		Central	Inte Range rval	
Agriculture, forestry, fishing & hunting	-37	50	-82	-53	65	-138
Mining, quarrying, oil & gas extraction	-45	62	-101	-59	73	-154
Utilities	-12	18	-30	-21	27	-58
Construction	-27	38	-63	-46	57	-122
Manufacturing	-44	51	-84	-102	116	-251
Transportation & warehousing	-31	33	-54	-60	62	-132
Total	**-197**	**251**	**-414**	**-342**	**400**	**-857**

Source: Data from Boyd et al. (2020)

Note: The **range** denotes the absolute lower (left) and upper (right) bound estimates. The lower bound estimate is generated by combining the lower confidence interval across all model inputs (i.e., the climate projections, the workforce projections, the exposure-response functions, and the projected economic unit values). In contrast, the upper bound estimate is generated by combining the upper confidence interval across all model inputs.

Table 16: Projected *annual* changes in labour productivity (value added) due to exposure of workers in “high-risk” industries to higher temperatures under RCP 4.5 ($ 2020 M)

Alberta	2050s			2080s		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-18	29	-39	-27	44	-66
Mining, quarrying, oil & gas extraction	-124	195	-266	-199	320	-484
Utilities	-21	32	-44	-43	68	-102
Construction	-83	133	-182	-156	252	-381
Manufacturing	-141	192	-264	-337	507	-766
Transportation & warehousing	-81	87	-119	-162	183	-275
Total	**-468**	**667**	**-913**	**-925**	**1,374**	**-2,074**

Manitoba	2050s			2080s		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-12	18	-26	-17	23	-40
Mining, quarrying, oil & gas extraction	-16	23	-34	-34	46	-83
Utilities	-14	21	-31	-20	28	-49
Construction	-34	52	-78	-67	94	-166
Manufacturing	-59	82	-122	-120	163	-290
Transportation & warehousing	-35	50	-75	-69	95	-169
Total	**-170**	**245**	**-365**	**-326**	**449**	**-797**

Saskatchewan	2050s			2080s		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-37	50	-82	-53	65	-138
Mining, quarrying, oil & gas extraction	-45	62	-101	-59	73	-154
Utilities	-12	18	-30	-21	27	-58
Construction	-27	38	-63	-46	57	-122
Manufacturing	-44	51	-84	-102	116	-251
Transportation & warehousing	-31	33	-54	-60	62	-132
Total	**-197**	**251**	**-414**	**-342**	**400**	**-857**

Source: Data from Boyd et al. (2020)

Note: The **range** denotes the absolute lower (left) and upper (right) bound estimates. The lower bound estimate is generated by combining the lower confidence interval across all model inputs (i.e., the climate projections, the workforce projections, the exposure-response functions, and the projected economic unit values). In contrast, the upper bound estimate is generated by combining the upper confidence interval across all model inputs.

Table 17: Projected *annual* changes in labour productivity (value added) due to exposure of workers in “high-risk” industries to higher temperatures under RCP 8.5 ($ 2020 M)

Alberta	2050s			2080s		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-27	44	-59	-62	99	-166
Mining, quarrying, oil & gas extraction	-191	303	-408	-482	773	-1,304
Utilities	-32	50	-68	-106	167	-282
Construction	-127	205	-278	-380	612	-1,032
Manufacturing	-223	306	-415	-829	1,250	-2,114
Transportation & warehousing	-125	137	-185	-401	450	-759
Total	**-725**	**1,044**	**-1,412**	**-2,259**	**3,351**	**-5,657**

Manitoba	2050s			2080s		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-17	24	-36	-36	49	-98
Mining, quarrying, oil & gas extraction	-23	33	-50	-77	104	-214
Utilities	-19	28	-42	-43	60	-122
Construction	-48	71	-108	-146	203	-415
Manufacturing	-82	112	-171	-262	352	-721
Transportation & warehousing	-48	69	-104	-151	206	-421
Total	**-238**	**337**	**-513**	**-714**	**973**	**-1,990**

Saskatchewan	2050s			2080s		
	Central	Range		Central	Range	
Agriculture, forestry, fishing & hunting	-55	73	-123	-114	137	-333
Mining, quarrying, oil & gas extraction	-67	91	-152	-127	153	-372
Utilities	-19	27	-46	-46	58	-141
Construction	-42	57	-96	-100	123	-299
Manufacturing	-69	79	-134	-224	255	-628
Transportation & warehousing	-48	50	-84	-132	133	-327
Total	**-300**	**378**	**-635**	**-745**	**859**	**-2,101**

Source: Data from Boyd et al. (2020)

Note: The **range** denotes the absolute lower (left) and upper (right) bound estimates. The lower bound estimate is generated by combining the lower confidence interval across all model inputs (i.e., the climate projections, the workforce projections, the exposure-response functions, and the projected economic unit values). In contrast, the upper bound estimate is generated by combining the upper confidence interval across all model inputs.

6 INFRASTRUCTURE

In this section evidence of the economic consequences of climate change for transportation and electricity T&D infrastructure on the Prairies is summarized. Economic impacts on buildings—another key component of the built environment—is presented in Section 7. While the impact of climate change on hydro-generation on the Prairies has been assessed, the results were not expressed in monetary terms and are thus not discussed below.

6.1 Transport infrastructure

Transportation systems consist of a vast, interconnected network of assets and derived services, that serve as the backbone of economic and social activity across the Prairies. But a changing climate undermines the system's ability to perform reliably, safely, and efficiently. Heavy precipitation and extreme heat events, and changes in average precipitation and temperature impact assets across all modes—road, rail, active and air—which threatens the performance of the entire network. Climate change will increase the costs of maintaining transport infrastructure—especially, as impacts compound.

Below, the scope of available economic analyses of the impacts of climate change on the Prairies' transportation infrastructure is presented along with the results. For a description of the methods employed—see Industrial Economics (2020)[31].

6.1.1 Scope of analysis

Industrial Economics (2020) assessed the economic impacts of climate change for a selection of Canada's infrastructure, including road and rail transportation networks. For roads and rail tracks, the following impacts, climate impact-drivers, and direct economic consequences were assessed:

Infrastructure	Climate impact-driver	Damage source	Economic consequence
Road lanes	High temperatures	Surface degradation and increased roughness due to thermal cracking and rutting	Increased repair and maintenance costs to maintain "levels of service"
	Heavy precipitation	Erosion of base and sub-base due to infiltration; increased cracking	Increased repair and maintenance costs to maintain "levels of service"
	Freeze-thaw cycles	Base layer degradation due to soil heaving; increased surface damage from settling and movement	Increased repair and maintenance costs to maintain "levels of service"

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[31] Industrial Economics, 2020: Costing Climate Change Impacts on Canada's Infrastructure: Results for "Deep Dive" Statistical and Process-based Models. Report prepared by Industrial Economics Limited for the Canadian Institute of Climate Choices.

Infrastructure	Climate impact-driver	Damage source	Economic consequence
Rail tracks	High temperatures	Track expansion and buckling under load	Increased repair and maintenance costs to maintain "levels of service"
Winter roads	Mean winter temperature	Usability of winter roads; assumed impassable if monthly mean temperature > minus 5°C	Cost of replacing winter roads with two-lane paved roads

In addition to direct damage costs, Industrial Economics (2020) also assessed the indirect costs borne by households (passenger movements) and businesses (freight movements) in the form of delay costs, assuming the introduction of speed restrictions on damaged roads and rails or during repairs.

6.1.2 Results

Projected future annual damages to roads, rail and winter roads on the Prairies due to climate change under RCP 4.5 and RCP 8.5 are shown in Table 18. Under the high emissions pathway (RCP 8.5) expected damages by mid-century are estimated at about $1.3B per year, rising to $2.8B per year by the end of the century. Damages to non-winter roads account for about 96%-98% of estimated total damages to linear transport infrastructure. Furthermore, damages are projected to be highest for Alberta, with the most extensive non-winter road network on the Prairies. In terms of the three climate impact-drivers assessed for non-winter roads, high temperature accounts for 78%-95% of total damages across both time periods and RCPs (Industrial Economics, 2020). The relative unit costs (damages per linear km) across the Prairies reflects the proportion of total non-winter roads in each province that are paved versus unpaved; paved roads are more vulnerable to temperature-related damage.

Regarding the rail network, damages are projected to be highest for Saskatchewan, with the most extensive rail network on the Prairies. The highest unit costs are also incurred in Saskatchewan, where a larger proportion of the network is exposed to higher temperatures. In absolute terms, damages to the rail network are small in comparison to the non-winter road network. The associated delay costs on the rail network (below) are nonetheless relatively more significant.

Regarding winter roads, it is evident from Table 18 that damages are higher in the first period under RCP 4.5 than the second period. This is because of how damages are measured—as the replacement of winter roads with paved roads—which is in effect a one-time adaptation measure. Hence, when a road is replaced in the first period it is no longer susceptible to warming in the second period; hence, costs are somewhat front-loaded.

Projected annual delay costs arising from damage to non-winter road and rail infrastructure on the Prairies due to climate change are shown in Table 19. Under the high emissions pathway (RCP 8.5) expected delay costs by mid-century are estimated at about $0.3B per year, rising to $0.9B per year by the end of the century. Delay costs thus account for about 20% (2050) to 25% (2080) of total costs, excluding impacts to winter roads. At the national level, total delay costs split approximately 53% (road) and 47% (rail) in 2050 and 46% (road) and 54% (rail) in 2080.

Table 18: Projected *annual* damages to road and rail infrastructure on the Prairies attributable to climate change under RCP 4.5 and RCP 8.5 ($ 2020 M and [$ per linear km])

Roads	RCP 4.5		RCP 8.5	
	2050	2080	2050	2080
Alberta	585 [1,105]	735 [1,395]	790 [1,500]	1,665 [3,155]
Manitoba	175 [770]	275 [1,205]	245 [1,085]	625 [2,770]
Saskatchewan	170 [445]	215 [560]	230 [595]	475 [1,235]
Total	**930** **[815]**	**1,225** **[1,075]**	**1,265** **[1,110]**	**2,770** **[2,430]**

Rail	RCP 4.5		RCP 8.5	
	2050	2080	2050	2080
Alberta	0.9 [145]	0.9 [145]	2.2 [345]	9.0 [1,385]
Manitoba	0.9 [180]	0.6 [135]	1.8 [380]	6.0 [1,250]
Saskatchewan	2.0 [245]	1.9 [235]	4.9 [595]	14.1 [1,725]
Total	**3.8** **[195]**	**3.5** **[180]**	**8.9** **[460]**	**29.1** **[1,495]**

Winter roads	RCP 4.5		RCP 8.5	
	2050	2080	2050	2080
Alberta	5 [12,520]	3 [7,195]	7 [17,580]	3 [6,660]
Manitoba	11 [4,252]	10 [4,300]	37 [15,230]	19 [7,750]
Saskatchewan	0 [0]	1 [2,860]	2 [9,060]	4 [17,165]
Total	**16** **[5,240]**	**14** **[4,575]**	**46** **[15,085]**	**25** **[8,300]**

Source: Data from Industrial Economics (2020)

Note: The sum of individual rows may not equal the column total due to rounding. Values in parenthesis show the ratio of projected damages per linear km of infrastructure in

Table 19: Projected *annual* delay costs arising from damage to road and rail infrastructure on the Prairies due to climate change under RCP 4.5 and RCP 8.5 ($ 2020 M)

Roads	RCP 4.5		RCP 8.5	
	2050	2080	2050	2080
Alberta	100 [15%]	155 [17%]	140 [15%]	405 [19%]
Manitoba	40 [19%]	55 [17%]	60 [20%]	185 [23%]
Saskatchewan	65 [27%]	70 [25%]	125 [35%]	345 [41%]
Total	**205** **[18%]**	**280** **[19%]**	**325** **[20%]**	**935** **[25%]**

Source: Data from Industrial Economics (2020)

Note: The sum of individual rows may not equal the column total due to rounding. Delay costs were not estimated for winter roads. Values in parenthesis show the contribution of delay costs total costs (i.e., damage plus delay costs)

6.2 Electricity T&D infrastructure

Climate change is anticipated to impact energy demand (see Section 7.2 below). It will also impact the entire value chain, including transmission and distribution (T&D). Electricity T&D infrastructure will likely be adversely affected by several climate impact-drivers, including: (a) increased temperatures, which increase line losses and reduce carrying capacity; (b) extreme precipitation events that increase the risk of flooding of ground level and underground assets; and (c) high winds, freezing rain, wildfires and heavy snow events that can damage poles and towers and down lines.

Industrial Economics assessed the economic impact of climate change for electricity T&D infrastructure in Canada, providing regionally disaggregated results that include the Prairie provinces. The scope of this analysis is presented along with the results. For a description of the methods employed—see Industrial Economics (2020).

6.2.1 Scope of analysis

For electricity T&D infrastructure in Canada, the following impacts, climate impact-drivers, and direct economic consequences were assessed in Industrial Economics (2020):

Asset	Climate impact-driver	Damage source	Economic consequence
Transformers[32]	Higher temperatures	Reduction peak load capacity and in expected useful life of asset	Costs of more frequent replacements and additional transformers
Lines	Higher temperatures	Reduction in ampacity of lines	Costs of constructing additional lines
Wood poles	Changes in precipitation and temperature	Increase rate of decay at base of wooden poles	Costs of more frequent replacements
Vegetation	Changes in precipitation and CO_2 concentrations	Modifications to the management of vegetation due to changes in growth and encroachment on assets	Increased O&M costs

Note that all asset replacements are assumed to be designed for the current climate as opposed to the historical climate and are thus more resilient to future climate change—though not as resilient as they could be if they were designed for projected climate change. Industrial Economics (2020) refers to this as a "reactive adaptation" scenario. As a result, the estimated damage costs presented below are lower than a pure "no adaptation" scenario, but higher than a proactive, planned adaptation scenario whereby asset replacements are designed to be resilient to future climate conditions.

6.2.2 Results

Projected annual damages to electricity T&D infrastructure on the Prairies attributable to climate change under RCP 4.5 and RCP 8.5 are shown in Table 20. Under the low (RCP 4.5) and high (RCP 8.5) emissions pathways expected damages by mid-century are estimated at about $355M and 450M per year, respectively. Under this "reactive adaptation" scenario, by the end of the century annual damages are estimated to decline to $160M (RCP 4.5) and $355M (RCP 8.5), as assets damaged earlier in the century are replaced by assets designed to a higher standard thereby reducing their susceptibility to the same climate hazards towards the end of the century.

Results for a "no adaptation" scenario are only available at the national level for 2080. Under this scenario, annual damages for Canada under RCP 8.5 are $2.9B compared with $1.5B under the "reactive adaptation" scenario—i.e., twice as high. Assuming the same ratio holds for the Prairies, that would put expected annual damages in the absence of adaptation by 2080 under RCP 8.5 at about $710M (2 x $355M). In terms of the distribution of damages across assets, the most impacted assets at the national level are: transformers (62% of total annual average damages in 2080 across both RCP 4.5 and RCP 8.5), lines (21%), poles (14%) and vegetation management (3%).

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[32] Both substation and distribution transformers were included in the assessment.

Table 20: Projected *annual* damages to electricity T&D infrastructure on the Prairies due to climate change under RCP 4.5 and RCP 8.5 assuming "reactive adaptation" ($ 2020 M)

Roads	RCP 4.5		RCP 8.5	
	2050	2080	2050	2080
Alberta	185	85	235	180
Manitoba	85	40	120	95
Saskatchewan	65	35	95	80
Total	**335**	**160**	**450**	**355**

Source: Data from Industrial Economics (2020)

Note: The sum of individual rows may not equal the column total due to rounding.

7 BUILDINGS

The economic impacts of climate change for buildings on the Prairies has been assessed for: (1) pluvial and fluvial flooding; and (2) space heating and cooling demand. Each is considered in turn below.

7.1 Flooding

Notwithstanding the potential consequences of inland flooding for public health and safety, crops and livestock, and infrastructure, flooding can result in significant damage to residential and commercial property. Losses arise from direct damage to both the structure and contents of buildings, as well as business inventories. Below, results from an analysis of the impact of climate change on inland flooding in Canada with disaggregated regional outcomes for the Prairies is presented.

7.1.1 Approach

In addition to the costs of climate change for Canada's transportation infrastructure, Industrial Economics (2020) also assessed damages at the Census Division level for both inland pluvial and fluvial flooding. The flood catastrophe models of JBA Risk Management were used as a basis for the analysis—providing: (a) average annual damage ratios for residential and commercial buildings (inclusive of both structural and contents damage); and (b) the number of residential and commercial buildings at risk—in both cases, for pluvial and fluvial flooding events in the absence of climate change. The JBA models are representative of exposures and flood risk mitigation measures adopted prior to 2016.

For the study, future flood damage costs were calculated by first fitting Gumbel extreme value distributions to baseline and projected maximum 1-day precipitation[33], and second, using the fitted distributions to scale the baseline average annual damage ratios in the JBA models. In effect, this generated four future precipitation-driven damage curves: (1) residential buildings-pluvial flooding; (2) residential buildings-fluvial flooding; (3) commercial buildings-pluvial flooding; and (4) commercial buildings-fluvial flooding. The adjusted, precipitation-driven average annual damage ratios (now including the influence of climate change) were then multiplied by the estimated structural and content value of all buildings at risk to calculate future damage costs[34].

7.1.2 Results

Projected future annual flood damages on the Prairies attributable to climate change under RCP 4.5 and RCP 8.5 are shown in Table 21. Under the latter—higher emissions pathway—expected damages by mid-

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[33] In the absence of hydrological flood models, it was necessary for Industrial Economics to develop damage curves based on precipitation as a proxy for flood depth. Given that flood depth is related to the square root of run-off—and to partially correct for the non-linear relationship between precipitation and flood depth—prior to fitting the Gumbel distributions maximum 1-day precipitation data was transformed to produce an "equivalent depth", which defined by the square root of maximum 1-day precipitation.

[34] In line with the FEMA HAZUS Flood Technical Manual (www.fema.gov/plan/prevent/hazus), contents were valued at 50% of the building value for residential structures and 100% of the building value for commercial structures.

century are estimated at about $1.2B per year, rising to $1.8B per year by the end of the century. Relative to estimated baseline damages, this represents roughly a 5-fold increase by 2050 and 7-fold increase by 2080. Based on historical asset valuations at the provincial level, Navius Research (2022) estimated that 70% and 30% of total flooding losses applied to the residential and commercial sectors, respectively[35]. Results for Calgary, Edmonton and Winnipeg are shown in Table 22. These three cities were among the 10 Census Subdivisions in Canada with the highest projected expected annual flood damages; the other Census Subdivisions were all in Ontario. The presence of both Calgary and Edmonton in the "top-ten list" for Canada also explains why Alberta accounts for 58%-68% of total projected annual damages on the Prairies, despite the relatively larger flood damages estimated for Winnipeg.

Table 21: Projected expected *annual* flood damages on the Prairies attributable to climate change under RCP 4.5 and RCP 8.5 ($ 2020 M)

Province	Baseline damages	RCP 4.5		RCP 8.5	
		2050	2080	2050	2080
Alberta	140	640 [4.5]	625 [4.4]	825 [5.8]	1,020 [7.2]
Manitoba	85	380 [4.5]	425 [5.1]	315 [3.8]	640 [7.6]
Saskatchewan	15	80 [5.8]	65 [4.8]	70 [4.9]	110 [7.9]
Total	**240**	**1,105** **[4.6]**	**1,120** **[4.7]**	**1,210** **[5.1]**	**1,770** **[7.4]**

Source: Data from Industrial Economics (2020)

Note: The sum of individual rows may not equal the column total due to rounding. Values in parenthesis show the ratio of projected damages with climate change compared to baseline damages

Table 22: Projected expected *annual* flood damages for Census Subdivisions on the Prairies with highest damages attributable to climate change under RCP 4.5 and RCP 8.5 ($ 2020 M)

Census Subdivision	Baseline damages	RCP 4.5		RCP 8.5	
		2050	2080	2050	2080
Calgary	40	200 [5.3]	200 [5.3]	200 [5.3]	245 [6.4]
Edmonton	35	140 [3.8]	135 [3.7]	115 [3.1]	150 [4.1]
Winnipeg	55	300 [5.3]	270 [4.8]	250 [4.4]	340 [6.0]

Source: Data from Industrial Economics (2020)

Note: Values in parenthesis show the ratio of projected damages with climate change compared to baseline damages

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[35] Navius Research, 2022, Evaluating the Macroeconomic Costs of Climate Change in Canada, Final Report prepared by Navius Research for the Canadian Institute for Climate Choices.

7.2 Heating and cooling demand

Climate change is anticipated to lead to: (a) a decrease in heating demand in the winter; and (b) an increase in cooling demand in the summer, with implications for annual energy costs. Whether annual building energy costs go up or down as a result of climate change will depend on the net effect of (a) and (b), the relative fuel mix of each end-use, and the future price of electricity vis-à-vis natural gas, all else being equal. Below, results from an analysis of the impact of climate change on electricity demand and expenditures in Canada with disaggregated regional outcomes is presented.

7.2.1 Approach

Navius Research (2020)[36] assessed the impact of climate change on *electricity* demand for space cooling and space heating, and corresponding changes in the frequency and intensity of peak electricity demand and associated costs in Canada. Projected changes in temperature across seven GCMs[37] and two climate scenarios (RCP 4.5 and RCP 8.5) were input to Navius' energy-economy model (gTech) and electricity model (Integrated Electricity Supply and Demand Model, IESD) to estimate the impact of climate change on electricity demand at 10-year increments from 2040 to 2100. gTech was used to determine annual electricity consumption by region, sector and end-use across Canada under 14 climate change scenarios (7 GCMs x 2 RCPs) relative to a projected baseline scenario with no climate change. All currently implemented and announced federal and provincial climate mitigation policies are included in the baseline scenario. Projected electricity consumption was subsequently input into IESD to quantify the impacts of climate change the electricity system; specifically, changes in peak electricity load, price and expenditures.

7.2.2 Results

Projected total annual electricity expenditures on the Prairies attributable to climate change under RCP 8.5 are shown in Table 23 at 10-year increments from 2040 to 2100. The change in total expenditures relative to the projected baseline case is also shown. Total expenditure includes capital investments and operating costs for fuel, labour, etc. These costs are ultimately recovered from end-users.

As electricity demand increases for space cooling and electricity price increases because of the corresponding increase in peak demand, total expenditures on the electricity system also rise. Total electricity system expenditures on the Prairies are projected to increase by about $95M and $1,020M annually by 2050 and 2100, respectively. This corresponds to increases of 1.3% and 5.4% compared with projected baseline expenditures in 2050 and 2100. Whether these increases in electricity demand for space cooling less reductions in electricity use for space heating[38] are offset by reductions in demand for natural gas (the main fuel for space heating on the Prairies) was not investigated[39]. Analysis for the City of

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[36] Navius Research, 2020, Impacts of Climate Change on Canada's Electricity System, Final Report prepared by Navius Research for the Canadian Institute for Climate Choices.

[37] The GCMs were selected to capture the range of uncertainty across the full ensemble of 24 GCMs for which projections are available.

[38] In 2019, electricity accounted for 12% of total energy use for space heating in the residential sector on the Prairies; 42% in Manitoba.

[39] Natural gas accounted for 83% of total energy use for space heating in the residential sector on the Prairies in 2019.

Edmonton shows increases in energy costs for increased space heating attributable to climate change are not offset by reductions in energy costs for space heating—considering net changes in both electricity and natural gas consumption[40].

Table 23: Projected changes in total *annual* electricity expenditures on the Prairies attributable to climate change under RCP 8.5 (based on median expenditures across all seven GCMs) ($ 2020 M)

	Alberta		Manitoba		Saskatchewan	
	Projected expenditure	Change from baseline	Projected expenditure	Change from baseline	Projected expenditure	Change from baseline
2040	3,065	21	2,079	12	1,079	18
2050	3,958	53	2,146	13	1,319	29
2060	4,825	61	2,301	87	1,553	51
2070	5,926	116	2,666	107	1,803	101
2080	6,922	241	3,711	345	2,058	133
2090	8,012	272	5,666	227	2,318	216
2100	9,761	344	7,733	409	2,537	265

Source: Data from Navius (2020), where results for RCP 4.5 can be found

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[40] Boyd, R., Costs of Inaction: Economic Analysis of Edmonton's Climate Risks, Summary prepared by All One Sky Foundation for the City of Edmonton, May 2022.

8 NATURAL SYSTEMS

Evidence of the economic impacts of climate change on natural systems on the Prairies is limited to the provisioning services provided the agricultural and forestry sectors.

8.1 Agriculture

The agricultural sector[41] contributed 1.66%, 5.45% and 8.11% to the GDP of Alberta, Manitoba and Saskatchewan, respectively, over the five-year period ending 2021. Climate change is anticipated to create both risks and opportunities for the agricultural sector in Canada[42]. Moderate levels of warming and increased carbon dioxide in the atmosphere could help some plants to grow faster or allow some farmers to shift to crops that are currently grown in warmer areas. However, more severe warming, and changes in the frequency and intensity of droughts and floods could pose challenges for farmers, reducing yields. Livestock may be at risk—directly from heat stress—and indirectly from reduced quality of their food supply. Climate change is also likely to increase the prevalence of parasites and diseases that affect livestock.

Several studies have estimated the economic impacts of climate change for the agricultural sector on the Prairies, while others have examined impacts for the sector in Canada—providing regionally disaggregated results for the Prairies. These studies are summarized in Table 24.

The available evidence suggests that the economic consequences of climate change for agriculture on the Prairies is likely to be positive and potentially significant—the exception being a small area of SE Alberta where one study projected decreases in farmland values. The estimated benefits—in particular those generated using Ricardian models of agricultural land values—should be viewed cautiously. For a start, the Ricardian models assume that the estimated relationships between monetary and climate variables embedded in the models are valid beyond the range of empirical evidence from which they were derived; this is unlikely be the case after mid-century. The estimated relationships also capture past adaptation behaviours by farmers. In the future, however, farmers are likely to face additional barriers to adaptation, thus reducing the efficacy of historical actions. Equally if not more important, none of the agricultural studies in Table 24 take account of the impacts of climate extremes (storms, flooding, drought) or changes in pests and disease on agricultural output and land values.

In general, studies using computable general equilibrium (CGE) models produce more conservative differing values, as they take account of trade with other regions which serves to lessen impacts. The same models show that GDP increases attributable to climate change impact on agriculture do not

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[41] Specifically, North American Industry Classification System (NAICS) Codes 11.1/2 [crop and animal production] and 11.51/52 [support activities for crop and animal productions].

[42] Lemmen, D., Lafleur, C., Chabot, D., Hewitt, J., Braun, M., Bussière, B., Kulcsar, I., Scott, D. and Thistlethwaite, J., 2021, Sector Impacts and Adaptation, Chapter 7 in Canada in a Changing Climate: National Issues Report, (ed.) Warren, F. and Lulham, N., Government of Canada, Ottawa, Ontario.

necessarily translate into proportional welfare gains for consumers—because of price increases, input substitution and trade effects.

Table 24: Summary of estimated economic impacts of climate change for the agricultural sector on the Prairies

Study	Scenarios	Physical and economic impacts considered	Results for the Prairies
Weber, M. and Hauer, G., 2003, A regional analysis of climate change impacts on Canadian agriculture, Canadian Public Policy, 29 (2), 163–180	Climate scenario based on single model run of the CGCMII model (Canadian Centre for Climate Modelling and Analysis) covering 1950–2070 (specific temp and precipitation changes not provided in paper) Static socioeconomic baseline based on Ricardian model of agricultural land values in Canada estimated for 1995–1996	Assessed impacts of monthly and quarterly projected temperature and precipitation changes (30-year average over 2021–2051) relative static 1995–1996 agricultural land values and farmland returns, using a Ricardian model with agriculture commodity prices fixed	Results show projected annual average changes in agricultural land values attributable to projected climate change (in 2020 dollars per ha): Alberta **+$2,930** Manitoba **+$2,235** Saskatchewan **+$2,930**
Ochuodho, T. and Lantz, V., 2015, Economic impact of climate change on agricultural crops in Canada by 2051: a global multi-regional CGE model analysis, Environmental Economics, 6 (1), 113-125	Climate scenario assumes changes in crop yields and agricultural land values over the period 2006 to 2051, derived from Weber and Hauer 2003 and Cline (2007)[43]. Socioeconomic baseline scenario of projected economic growth (in the absence of climate change) over the period of 2006–2051	Assessed the impact of climate change on crop yields (under climate scenario relative to projected baseline scenario) and in turn on provincial macroeconomic indicators, using a multi-regional computable general equilibrium (CGE) model, including trade with the USA and rest of the world	Results show the projected % change in the present value of cumulative provincial GDP (discounted at 4% per year) over the period 2006-2051: Alberta: **+2.5%** Manitoba: **+1.3%** Saskatchewan: **+0.5%**

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[43] Cline, W., 2007, Global warming and agriculture: impact estimates by country, Peterson Institute of International Economics, Washington, DC, 250 pp.

Study	Scenarios	Physical and economic impacts considered	Results for the Prairies
Amiraslany, A., 2010, The impact of climate change on Canadian agriculture: a Ricardian approach. Doctoral dissertation, Department of Bioresource Policy, Business and Economics, University of Saskatchewan, Saskatoon, SK, 169 pp	Climate scenario assumes mean annual temperature increases (relative to 1961–1990 climate norm) over the Prairies of +1.05°C (by 2020), +2.19°C (by 2050) and +3.26°C (by 2080); and precipitation changes of +0.016 mm per day (by 2020); +0.116 mm per day (by 2050) and +0.186 mm per day (by 2080) Static socioeconomic baseline based on Ricardian model of farmland values estimated from 1991, 1996 and 2001 data, though projected changes in crop prices were included	Assessed impacts of uniform increase in temperature and precipitation (relative to 1961–1990 norm) on static farmland values (using a Ricardian model) Analysis incorporated the impacts of projected changes in wheat and canola prices with climate change based on values from literature (+5% by 2020, +15% by 2050 and +25% by 2080)	Results show projected annual average changes in farmland values attributable to projected climate change, including changes to land values (2020 dollars per ha) and % planted area for Prairies: Average over Alberta, Manitoba and Saskatchewan: **+$240** and **+15%** (by 2020); **+$635** and **+40%** (by 2050); and **+$830** and **+50%** (by 2080) However, decreases in farmland values are projected for areas of SE Alberta in all future time periods
Ayouqi, H. and Vercammen, J., 2014, Evaluating the impact of climate change on Canadian prairie agriculture, LEARN Linking Environment and Agriculture Research Network, Research Project PR-01-2014, University of British Columbia, Vancouver, 18 pp	A single climate scenario is considered, based on projected temperature and precipitation changes under IPCC SRES A2 emissions scenario relative to the 1971-2000 climate norm (from CGCM model only): mean annual temperature change = +1.3°C (by 2020s), +2.6°C (by 2050s) and +4.1°C (by 2080s); mean annual precipitation change = +5% (by 2020s), +12% (by 2050s) and +17% (by 2080s) Static socioeconomic baseline based on Ricardian model of farmland values estimated from 1991, 1996, 2001, 2006 and 2011 data, though projected changes in crop prices were included	Assessed impacts of uniform increase in temperature and precipitation (relative to 1971–2000 norm) on static farmland values, using a Ricardian model Model also included impacts of projected changes in wheat, canola, alfalfa, barley and cattle prices with climate change derived from literature (+5% by 2020, +15% by 2050 and +25% by 2080)	Results show the projected annual average changes in aggregate farmland values attributable to climate change (2020 dollars) for Prairies: Alberta, Manitoba and Saskatchewan: **+$1.7B** to **+$2.4B** per year by the 2020s; **+$2.8B** to **+$3.9B** per year by the 2050s and **+$2.7B** to **+$5.9B** per year by the 2080s, depending on Ricardian model specification used

Source: Adapted from Boyd and Markandya (2021)[44]

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[44] Boyd, R. and Markandya, A., 2021, Costs and Benefits of Climate Change Impacts and Adaptation; Chapter 6 in Canada in a Changing Climate: National Issues Report, (Eds.) Warren, F. and Lulham, N., Government of Canada, Ottawa, Ontario.

8.2 Forestry

The forestry sector[45] contributed 0.18%, 0.09% and 0.20% to the GDP of Alberta, Manitoba and Saskatchewan, respectively, over the five-year period ending 2021. Many climate impact-drivers are likely to—directly or indirectly—affect the forestry industry on the Prairies[46]. Climate change is anticipated to alter the frequency and intensity of forest disturbances, such as wildfires, storms, insect outbreaks, and the prevalence of invasive species. Increases in temperature, changes in precipitation, and increases in carbon dioxide are likely to impact the growth and productivity, as well as the distribution of forests.

Several studies have examined the economic impacts of climate change for the Canadian forestry sector, providing regionally disaggregated results for the Prairies. These studies are summarized in Table 25. Climate change is projected to adversely impact timber supply leading to reduced forest sector output and value added (GDP) on the Prairies. Climate change is also projected to increase fire suppression costs well above historic levels, with Alberta and Saskatchewan seeing significant increases in costs relative to the national average.

Table 25: Summary of estimated economic impacts of climate change for the forestry sector on the Prairies

Study	Scenarios	Physical and economic impacts considered	Results for the Prairies
NRTEE, 2011, Paying the price: the economic impacts of climate change for Canada. National Round Table on the Environment and the Economy (NRTEE), Ottawa, Ontario, 162 pp	A combination of two climate and two socioeconomic scenarios Changes in mean annual temperature for Canada by 2050 under low (IPCC SRES B1) (+3.4°C) and high (IPCC SRES A2) (+3.6°C) climate scenarios Projected GDP growth for Canada by 2050 under a slow-growth (+1.3% per year) and rapid-growth (+3.0% per year) scenario	Physical impacts on timber supply from forest fires, pests and diseases, changes in forest productivity relative to projected "no climate change" baselines (driven by slow- and rapid-growth scenarios) Changes in projected GDP relative to "no climate change" baseline, using CGE model	Results show annual GDP losses by 2050 (undiscounted 2020 dollars and % reduction in projected baseline GDP): Alberta: **$0.2B** (low climate-slow growth scenario) to **$1.0B** (high climate-rapid growth scenarios), or reductions of **0.06%** to **0.14%** of baseline GDP Aggregation of Manitoba, Saskatchewan, Yukon and Northwest Territories: **$0.6B** (low climate-slow growth scenario) to **$3.6B** (high climate-rapid growth scenario), or reductions of **0.33%** to **0.85%** of baseline GDP

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[45] Specifically, North American Industry Classification System (NAICS) Codes 11.3 [forestry and logging] and 11.53 [support activities for forestry].

[46] Sauchyn, D., Davidson, D., and Johnston, M, 2020, Prairie Provinces, Chapter 4 in Canada in a Changing Climate: Regional Perspectives Report, (ed.), Warren, F. Lulham, N. and Lemmen, D., Government of Canada, Ottawa, Ontario.

Study	Scenarios	Physical and economic impacts considered	Results for the Prairies
Ochuodho, T., Lantz, V. A., Lloyd-Smith, P. and Benitez, P., 2012, Regional economic impacts of climate change and adaptation in Canadian forests: a CGE modeling analysis, Forest Policy and Economics, 25, 100-112	A combination of two climate and two socioeconomic scenarios Changes in mean annual temperature for Canada by 2050 under low (IPCC SRES B1) (+3.4°C) and high (IPCC SRES A2) (+3.6°C) climate scenarios Projected GDP growth for Canada by 2050 under a slow-growth (+1.3% per year) and rapid-growth (+3.0% per y ear) scenario	Pessimistic (worst-case) and optimistic (best-case) physical impacts on timber supply from forest fires, pests and diseases, changes in forest productivity relative to projected "no climate change" baselines (driven by slow- and rapid-growth scenarios) Changes in projected sector output values, GDP and welfare (compensating variation) relative to "no climate change" baseline, using CGE model	Results show present-value cumulative GDP losses in 2020 dollars over the period 2010-2080, discounted at 3% discount rate: Alberta: **$1.1B** (low climate, slow growth, optimistic scenario) to **$21.3B** (high climate, rapid growth, pessimistic scenario) Aggregation of Manitoba, Saskatchewan, Yukon and Northwest Territories: **$4.6B** (low climate, slow growth, optimistic scenario) to **$79.8B** (high climate, rapid growth, pessimistic scenario)
Hope, E., McKenney, D., Pedlar, J., Stocks, B. and Gauthier, S., 2015, Wildfire suppression costs for Canada under a changing climate, PLoS ONE, 11 (8), e0157425	Changes in the 4-month sum (May-August) of the Climate Moisture Index (CMI) projected by four GCMs under RCP 2.6 and RCP 8.5 relative to the 1961-1990 climate normal No socioeconomic change scenarios were considered; baseline suppression costs are held constant in real terms at 2009 dollars over the projection period	Changes in the area burned were estimated as a function of projected changes in the CMI under each climate scenario Changes in fixed and variable fire suppression costs (relative to the annual average costs incurred in 1980-2009) were estimated as a function of projected changes in the area burned	Results show that the two most affected provinces are Alberta and Saskatchewan—in terms of the projected % change in annual average total suppression costs by the 2080s: Alberta: under RCP 2.6 and RCP 8.5 total annual suppression costs incurred over the period 1980-2009 are projected to increase by **141%** and **195%**, respectively Saskatchewan: under RCP 2.6 and RCP 8.5 total annual suppression costs incurred over the period 1980-2009 are projected to increase by **218%** and **265%**, respectively

Source: Adapted from Boyd and Markandya (2021)

9 CITY-LEVEL CASE STUDIES

Detailed economic analyses of the physical impacts of climate change were recently completed for both the City of Edmonton and the City of Calgary[47]. In both cases the purpose was to communicate the magnitude of the potential economic risks to senior leadership and the Council to (a) support urgent investment in climate adaptation and (b) provide a baseline for assessing the benefits of, and returns on, that investment. The scope and results of these assessments are summarized in this section; the approach employed to generate these results was outlined in Section 2.1.

9.1 Scope of analysis for Calgary and Edmonton

In both assessments, economic impacts were quantified for 2025, 2055and 2085[48]. For each of these years, economic impacts were calculated for projected changes in relevant climate impact-drivers compared to the 1981-2010 climate baseline used by each city. Estimated costs for 2025 are thus really the expected annual costs of impacts to (say) roads attributable to climate change between 1981-2010 and 2025. Likewise, estimated impacts to roads in 2055 represent the expected annual costs attributable to climate change between 1981-2010 and 2055. Primary interest concerns the difference in estimated economic impacts between 2025 and 2055 and between 2025 and 2085, as these differences represent the costs attributable to further climate change beyond what is currently experienced in both cities.

The analyses were performed for projected climate change under RCP 8.5. When assessing climate-related economic risks it is prudent to consider the greatest plausible change scenario relative to the present, which meant working with the RCP 8.5 scenario (i.e., the most conservative of global “no climate policy” scenarios). The primary justification for using RCP 8.5 is that it minimizes the risk of missing material economic impacts. Uncertainties relating to whether the future unfolds along RCP 8.5 or along a different, lower emission pathway, can be managed when subjecting adaptation strategies and measures to economic analysis.

The climate-sensitive human and natural systems, climate impact-drivers and economic consequences included within scope of the assessments for each city are shown in Table 26. As noted in Section 2.2, both ecosystem services, time delays (the value of time) and welfare losses arising from adverse health outcomes are direct “intangible costs”; all other economic consequences listed in Table 26 are direct “tangible costs”.

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[47] Boyd, R. and Prescott, S., Costs of Inaction: Economic Analysis of Calgary’s Climate Risks, Summary Report prepared by All One Sky Foundation for the City of Calgary, April 2022; and Boyd, R., Costs of Inaction: Economic Analysis of Edmonton’s Climate Risks, Summary Report prepared by All One Sky Foundation for the City of Calgary, May 2022.

[48] Strictly speaking, impacts are calculated as the 30-year average over the periods 2011-2040 (central year = 2025), 2041-2070 (central year = 2055), and 2071-2100 (central year = 2085).

Table 26: Climate-sensitive systems, climate impact-drivers and direct economic consequences included within scope of assessments for Calgary and Edmonton

Exposed human and natural systems	Climate impact-drivers	Economic consequences	Calgary	Edmonton
Roads	High temperatures, heavy precipitation, freeze-thaw cycles	Damages	✓	✓
	High temperatures, heavy precipitation, freeze-thaw cycles	Delays (value of time)	✓	✓
LRT rails	High temperatures	Damages	✓	✓
Active transport network	High temperatures, drought, extreme cold, freeze-thaw cycles, pluvial flooding	Damages		✓
Buildings	Fluvial and pluvial flooding	Damages to structure and contents, evacuations	✓	✓
	Hailstorm, high winds, freezing rain, freeze-thaw cycles, heavy snow	Damages	✓	✓
	Heating degree days, cooling degree days	Energy costs	✓	✓
Electricity T&D (linear)	High temperatures, hailstorm, high winds, freezing rain, heavy snow, pluvial flooding, river flooding, wildland fire	Damages	✓	✓
Potable water (linear)	Cold temperatures, drought, freeze-thaw cycles	Damages	✓	✓
Potable water (plant)	River flooding, extreme cold	Damages		✓
Wastewater (linear)	Freeze-thaw cycles, pluvial flooding	Damages	✓	✓
Wastewater (plant)	River flooding	Damages		✓
Drainage (linear)	Freeze-thaw cycles, pluvial flooding	Damages	✓	✓
City trees	High temperatures, drought, heavy snow, freezing rain, high winds, wildland fire, tornado, lightning	Damages	✓	✓
		Ecosystem services	✓	✓
Natural areas	High temperatures, drought, extreme cold, hailstorm, high winds, freezing rain, heavy snow, pluvial flooding, river flooding, wildland fire, tornado	Damages	✓	✓
		Ecosystem services	✓	✓
Labour	High temperatures	Lost output	✓	✓
Public health	Air quality (ground-level ozone) - acute mortality	Welfare losses	✓	✓
	Air quality (ground-level ozone) - acute mortality	Lost output	✓	✓
	Air quality (ground-level ozone) - chronic mortality	Welfare losses	✓	✓
	Air quality (ground-level ozone) - chronic mortality	Lost output	✓	✓
	Air quality (ground-level ozone) - morbidity	Welfare losses	✓	✓
	High temperatures - mortality	Welfare losses	✓	✓
	High temperatures - mortality	Lost output	✓	✓
	High temperatures - hospitalizations	Healthcare costs	✓	✓
	High temperatures - hospitalizations	Lost output	✓	✓
	Exacerbation of mental health disorders - multiple climate impact-drivers	Welfare losses		✓
	Other public health and safety impacts - multiple climate impact-drivers	Welfare losses		✓

Source: Boyd and Prescott (2022) and Boyd (2022)

Note: The following climate impact-drivers were only included in the assessment for the City of Edmonton: wildfire, tornado, lightning

9.2 City-level costs of climate change

Expected annual (tangible and intangible) costs for the Calgary and Edmonton in 2025 are estimated at \$0.7B and \$1.3B, respectively. Notwithstanding the larger inventory of human and natural systems being exposed to climate impact-drivers in Calgary, the difference in costs is primarily due to more climate-sensitive sectors and climate impact-drivers being included in the analysis for Edmonton—in particular, welfare losses associated with the exacerbation of mental health disorders. For both Calgary, the split between tangible and intangible losses in 2025 is, respectively, about 48% versus 52%. Clearly, when assessing the economic impacts of climate change and setting priorities for adaptation, the importance of including intangible costs cannot be overstated.

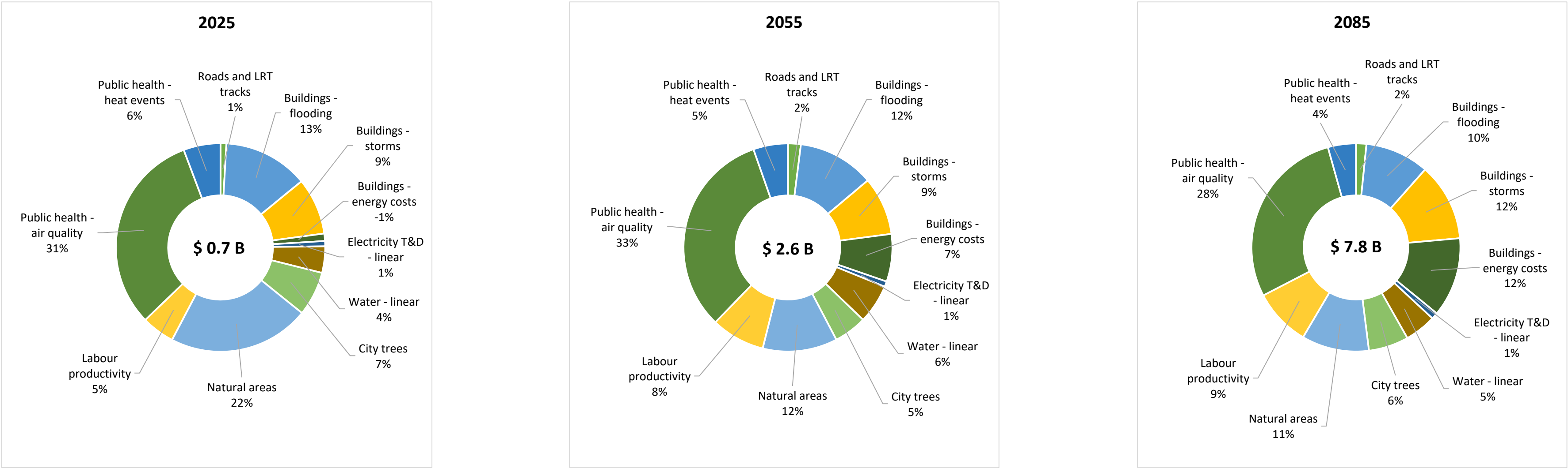
Further climate change beyond 2025 under RCP 8.5 is projected to increase total annual costs in Calgary by \$1.9B (to \$2.6B) by 2055 and by \$7.1B (to \$7.8B) by 2085. Similar increases are projected for Edmonton, with total annual costs estimated to increase by \$2.0B (to \$3.3B) by 2055 and by \$7.0B (to \$8.4B) by 2085. These increases are driven by both climate change and socioeconomic growth—placing more systems at risk with higher valuations. The split between tangible and intangible losses by 2085 in Edmonton shifted slightly—now about 52% (tangible costs) versus 48% (intangible costs), mainly driven by growth the value of buildings exposed to climate impact-drivers. In Calgary, however, tangible costs account for about 60% of total damages by 2085, up from 48% in 2025—driven largely by projected growth in the value of road and utility infrastructure.

The breakdown of total annual costs by exposed system for both cities in 2025, 2055 and 2085 is shown in Figure 8. When viewing the contents of the figure, note that economic impacts are increasing for all exposed systems over the course of the century, even though the contribution of individual systems to total costs is shown to decline between 2025 and 2055 and 2085. One of the largest sources of loss for both Calgarians and Edmontonians in all three time periods is deteriorating air quality associated with increased concentrations of ground-level O_3 as temperatures rise. This is primarily due to excess deaths from acute exposures of the population to ground-level O_3. By mid-century, damage to buildings from flooding and storm events emerge as the next most significant source of loss.

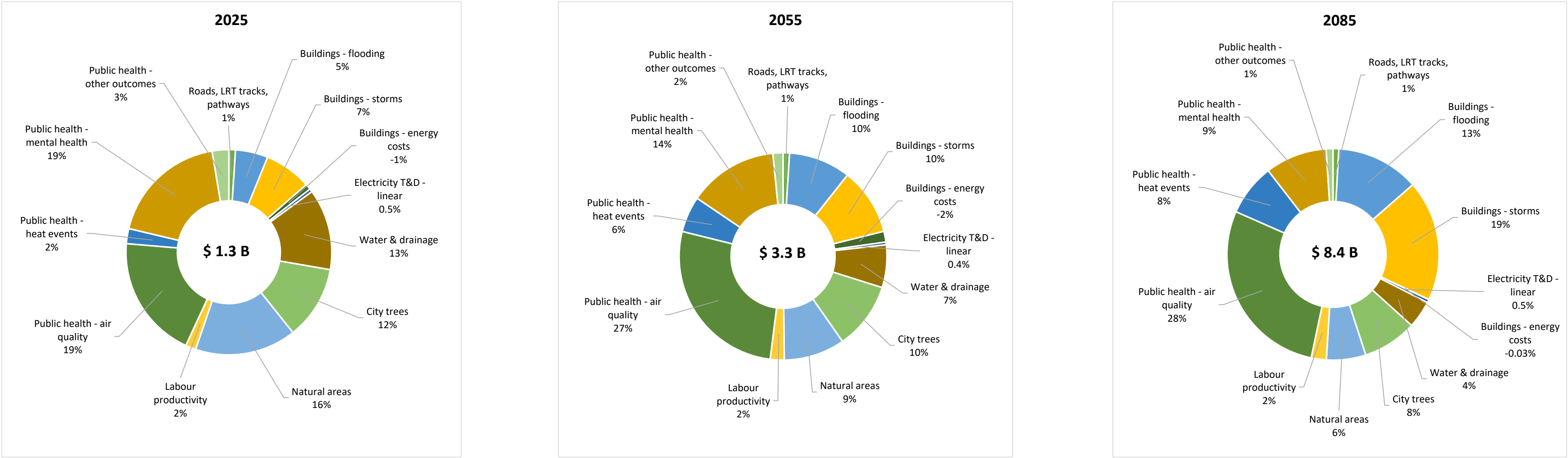
Other important sources of loss from the climate impact-driver considered include damage to the natural assets (i.e., the City trees and natural areas, such as forested areas, shrublands, grasslands and wetlands) and associated loss of ecosystem services—and for Edmonton—adverse impacts on the mental health of residents—primarily from exposure to high temperatures and drought events. In generally, public health impacts collectively represent the largest source of loss in both cities, accounting for 33%-51% of total losses in all three time periods.

Figure 8: Projected direct *annual* tangible and intangible costs of climate change for a future Calgary and Edmonton in 2020, 2055 and 2085 by climate-sensitive system ($ 2020)

City of Calgary



City of Edmonton



Source: Boyd and Prescott (2022) and Boyd (2022)

To isolate the role climate change plays relative to socioeconomic change in driving the magnitude of costs, consider Figure 9, which shows the projected total direct economic impacts of climate change for a future Calgary and Edmonton, across all systems, climate impact-drivers and tangible and intangible impacts considered (recall Table 26). Looking at Calgary, for example, the figures are interpreted as follows:

$0.7B	=	The expected annual direct economic cost in 2025 (based on population, assets, land-use and valuation projections for 2025) because of changes in the climate between the 1981-2010 baseline period and the 30-year period (2011-2040) centered on 2025.
$1.3B	=	The expected annual direct economic cost in 2055 (keeping the city's systems at 2025 levels) because of projected changes in the climate between the 1981-2010 baseline period and the 30-year period (2041-2070) centered on 2055. Put another way, the projected climate for the 2050s is overlaid on today's Calgary.
+$0.8B	=	The change in annual direct economic costs between 2025 and 2055 as a result of climate change, assuming exposed systems remains at 2025 levels.
$1.4B	=	The expected annual direct economic cost when projected changes in the climate between the 1981-2010 baseline period and the 30-year period (2011-2040) centered on 2025 are overlaid on Calgary's projected population, assets, land-use and associated values in 2055.
+$0.7B	=	The change in annual direct economic costs between 2025 and 2055 as a result of socioeconomic change in Calgary, assuming no further climate change beyond 2025.
$2.6B	=	The expected annual direct economic cost in 2055 when projected changes in the climate between the 1981-2010 baseline period and the 30-year period (2041-2070) centered on 2055 are overlaid on Calgary's projected population, assets, land-use and associated values in 2055. Put another way, the projected climate of the 2050s is overlaid on a future projection of Calgary in the 2050s.
+$1.2B	=	The imposed direct annual costs of climate change. That is, the additional economic risk (in dollar terms) climate change poses a future Calgary in 2055 in the absence of any new autonomous or planned adaptation.

The values for 2085 are interpreted similarly. It is worth stressing again (as per Section 2.1) that adaptation strategies and measures seek to reduce total economic risk and not solely the fraction attributable to climate change.

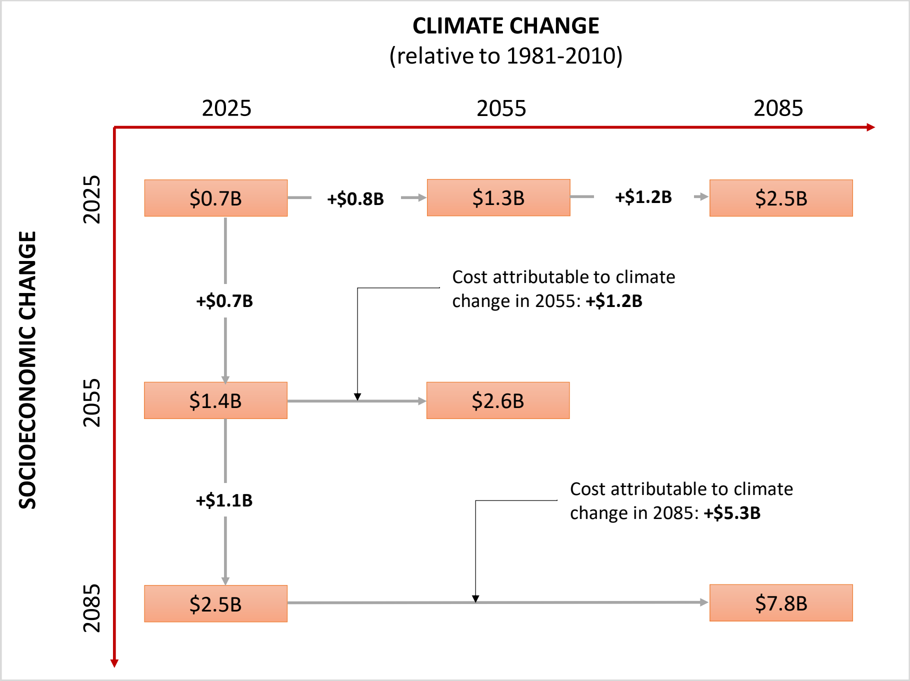
For each city, Figure 9 shows that in the absence of any new autonomous or planned adaptation:

- The imposed direct annual costs of climate change for Calgary are estimated at about $1.2B and $5.3B (2020 dollars) in 2055 and 2085, respectively.
- The imposed direct annual costs of climate change for Edmonton are estimated at about $1.0B and $4.1B (2020 dollars) in 2055 and 2085, respectively.

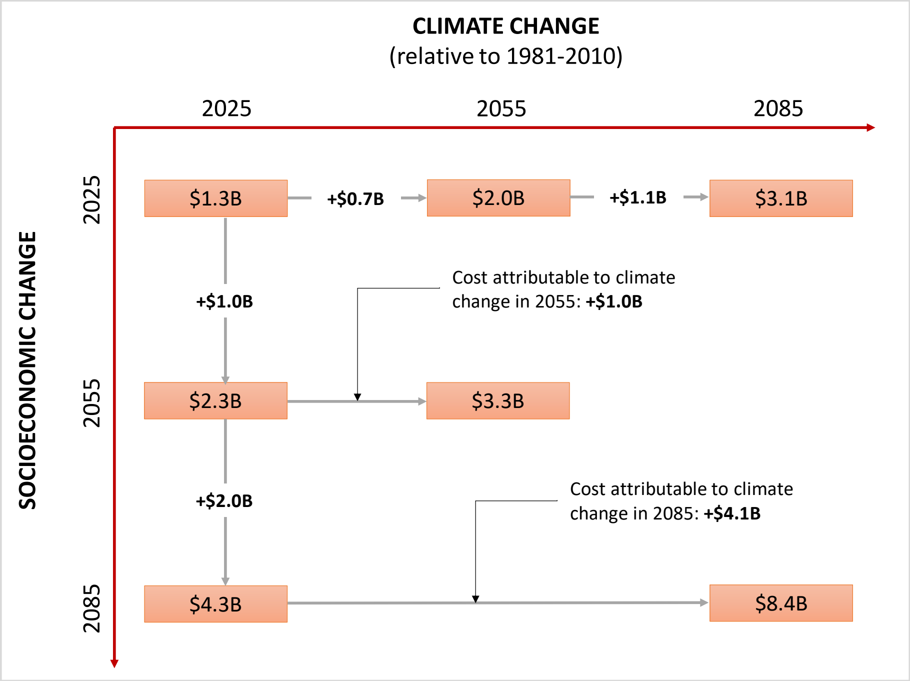
In other words, in the 2050s and 2080s expected total losses attributable to projected changes in Calgary's (Edmonton's) climate are anticipated to amount to, respectively, $1.2B ($1.0B) and $5.3B ($4.1B) on average in any given year.

Figure 9: Projected aggregate *annual* (tangible and intangible) economic costs of climate change for Calgary and Edmonton, by socioeconomic and climate drivers

City of Calgary



City of Edmonton



Source: Boyd and Prescott (2022) and Boyd (2022)

The estimated direct annual tangible costs were input to a regionalized, city-specific Input-Output model to gain some insights into the associated wider macroeconomic consequences of climate change impacts in each city. As explained in Section 2.1, these macroeconomic impacts represent the 'opportunity costs' of diverting resources away from other productive uses in the economy to—for example—repair damaged buildings or infrastructure. In the absence of further climate change these costs would not be incurred.

The results are shown in Table 27. The overall (direct, indirect and induced) impact of climate change for gross output by mid-century is estimated at $5.2B (Calgary) to $5.5B (Edmonton) annually. By the 2080s, the overall opportunity cost of climate change for gross output is projected to amount to $16.4B (Calgary) to $15.4B (Edmonton) annually. Looking at value-added, annual GDP losses due to climate-related impacts on each city in 2055 and 2085 are estimated at, respectively, $2.2B (both Calgary and Edmonton) and $7.0B (Calgary) to $6.2B (Edmonton).

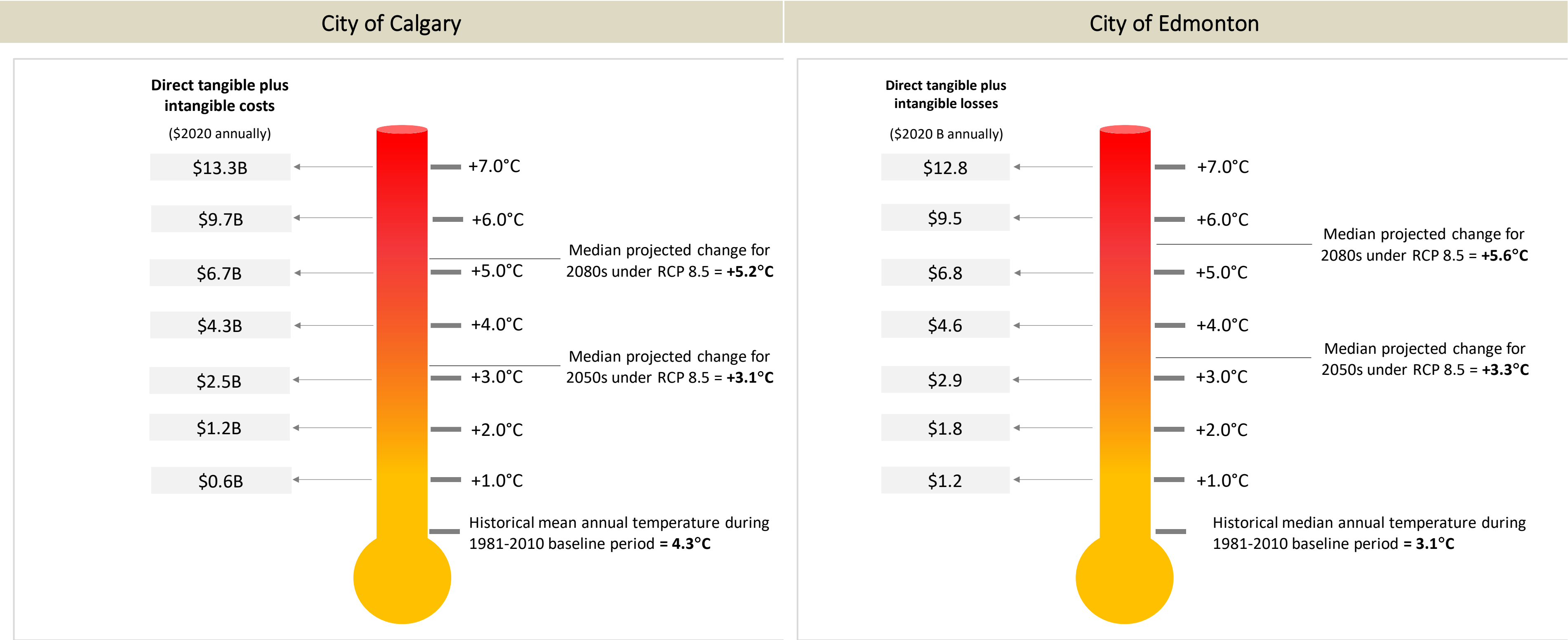
Table 27: Projected direct, indirect and induced *annual* tangible costs of climate change for a future Calgary and Edmonton, by time period ($ 2020 B)

Macroeconomic indicator	City of Calgary			City of Edmonton		
	2025	2055	2085	2025	2055	2085
Tax revenues	0.3	0.1	0.5	0.1	0.1	0.5
Labour income	0.3	1.2	3.6	0.5	1.3	3.5
Gross output	1.3	5.2	16.6	2.2	5.5	15.4
GDP	0.5	2.2	7.0	0.9	2.2	6.2

Source: Boyd and Prescott (2022) and Boyd (2022)

To illustrate the economic consequences for each city from different levels of climate change relative to the 1981-2010 baseline period, a relationship between estimated direct total annual damages and projected changes in mean annual temperature was estimated. The estimated relationship was subsequently used as a basis to create the thermometers shown in Figure 10. Each thermometer shows the estimated direct annual tangible and intangible costs associated with one degree Celsius increments in mean annual temperature relative to the baseline period. For reference, the projected mean annual temperature for each city for the 2050s and 2080s under RCP 8.5 are also shown. By way of example, if Calgary (Edmonton) develops as projected and the climate continues to change in accordance with RCP 8.5, then when changes in mean annual temperature reach +4°C above baseline levels, total direct tangible and intangible losses are estimated at about $4.3B ($4.6B), on average, per year.

Figure 10: Projected aggregate economic impacts of different amounts of future climate change for Calgary and Edmonton (direct tangible and intangible costs) ($ 2020 B annually)



Source: Boyd and Prescott (2022) and Boyd (2022)

10 SUMMARY AND KNOWLEDGE GAPS

Several studies have investigated the costs of climate change for a range of climate-sensitive sectors in Canada, with regionally disaggregated results covering the Prairies. A few studies have examined costs for the agricultural sector on the Prairies. Two detailed cost analyses have also been completed for the City of Edmonton and the City of Calgary. The goal of this report was to synthesize the results of these studies into a single compendium of the costs climate change for the Prairies reflecting the current state-of-knowledge. A summary of available cost estimates for the Prairies and key knowledge gaps is presented below.

10.1 Summary of findings

Typically, it is far from straightforward to compare the relative magnitude and significance of the costs of climate change between climate-sensitive sectors or to aggregate across sectors because of differences in assumptions and methodologies across studies. Key differences between studies that influence the results and make aggregation and comparisons difficult include:

- The choice of climate scenario(s) driving the biophysical impacts, as well as the future and baseline periods used to measure changes in relevant climate impact-drivers;
- Assumptions regarding future socioeconomic developments, which will influence both the quantity and monetary valuation of exposed human systems and the environment; and
- The types of economic costs measured—whether direct tangible or intangible impacts or impacts to macroeconomic indicators like GDP; and relatedly
- The choice of economic modelling tool—each with their own set of strengths and weaknesses—e.g., process-based models (for public health and infrastructure), Ricardian models (for agricultural sector) or CGE models (for forestry).

A research program recently completed for the Canadian Climate Institute sought to address these shortcomings, creating a comparable data set based on common assumptions, climate and socioeconomic scenarios, and methods. With the exception of agriculture and forestry, most of the information presented above is drawn from this program of work. Table 28 provides a summary of comparable and additive results for each Prairie province for the 2050s and 2080s under the high emissions pathway, RCP 8.5. Across the climate-sensitive sectors listed in the table, the direct annual (tangible and intangible) costs of climate change for the Prairies in the 2050s and 2080s are estimated at about $15.7B and $37.4B, respectively. In both time periods, over half these costs result from biophyscial impacts in Alberta—due to the larger projected “stock-at-risk” in Alberta relative to Manitoba and Saskatchewan. However, on a per capita basis, the largest projected annual costs in both time periods occur in Manitoba ($2,235-$3,680 per person), followed by Saskatchewan ($1,875-$3,330 per person), then Alberta ($1,300-$2,230 per person) (see Table 29). This suggests that the projected changes in climate impact-drivers above specific threshold levels[49] for Manitoba and Saskatchewan are higher than for Alberta.

Table 28: Synthesis of estimated direct *annual* economic (tangible and intangible) impacts of climate change for the Prairie provinces under high emissions pathway, RCP 8.5 ($ 2020 M)

	2050s			2080s		
	AB	MB	SK	AB	MB	SK
Ozone - acute mortality	3,800	1,600	1,500	10,000	3,600	3,800
Ozone - chronic mortality	2,000	700	700	5,700	1,600	1,900
Ozone - morbidity	40	132	11	118	32	30
High temperatures - mortality	295	155	135	745	340	335
High temperatures - morbidity	20	4	5	56	11	14
Lyme disease	0	440	0	0	645	0
Workforce – compensation	359	128	197	1,116	390	342
Workforce - GDP	725	238	300	2,259	714	745
Non-winter roads - damages	790	245	230	1,665	625	475
Rail - damages	2	2	5	9	6	14
Winter roads - damages	7	37	2	3	19	4
Transport - delays	140	60	125	405	185	345
Electricity T&D infrastructure	235	120	95	180	95	80
Buildings - flooding	825	315	70	1,020	640	110
Electricity demand	57	50	40	257	286	175
Total	8,570	3,990	3,115	21,275	8,475	7,625

Note: For estimated impacts on the workforce, only lost compensation (as a proxy for the value of lost output) is included in the totals as GDP is not additive with the other measures of loss in the table. Estimated costs for electricity T&D infrastructure decrease from the 2050s to the 2080s because the analysis assumed some level of adaptation when assets are repaired or replaced in early years (recall Section 6.2.2).

Across the climate impact drivers-sectors for which comparable results are available, economic impacts arising from premature deaths attributable to worsening air pollution caused by rising temperatures account for roughly two-thirds of total losses over both periods. Other public health impacts (due to high temperatures and Lyme disease) account for a further 6%-7% of total losses. Damages and transport delays resulting from climate-related impacts to assets and infrastructure represent about 18%-22% of total losses, with non-winter roads anticipated to experience the largest damages. Finally, forgone output from the exposure of the Prairies' workforce to high temperatures is projected to account for 4%-5% of total losses.

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[49] For example, the exposure-response functions used to estimate the impact of temperature extremes on labour supply (hours worked) start measuring impacts above daily highs of 24°C.

Table 29: Aggregate and per capita direct *annual* economic impacts of climate change for the Prairies under high emissions pathway, RCP 8.5 (2020 dollars)

	2050s		2080s	
	($M)	($ per capita)	($M)	($ per capita)
Alberta	8,570	1,300	21,275	2,230
Manitoba	3,990	2,235	8,475	3,680
Saskatchewan	3,155	1,875	7,625	3,330
Total	**15,675**	**1,565**	**37,370**	**2,645**

Note: The estimated per capita costs are based on projected provincial populations for 2055 and 2085.

Several studies have also examined the economic impacts of climate change for the Canadian agriculture and forestry sectors, providing results for the Prairies. These results, however, are not additive to those presented in Table 28 due to—among other things—differences in the underlying climate scenarios and timeframes. The available evidence suggests that the economic consequences of climate change for agriculture on the Prairies are likely to be positive and potentially significant. For example, one study anticipates climate change (under a high emissions pathway) will increase aggregate farmland values across the Prairies by $2.8B-$3.9B per year (2020 dollars) by the 2050s and $2.7B-$5.9B per year (2020 dollars) by the 2080s, depending on modelling assumptions. Another study suggests the present value of cumulative provincial GDP over the period 2006-2051 under a high emissions pathway relative to a no climate change baseline will increase by 2.5% in Alberta, 1.3% in Manitoba and 0.5% in Saskatchewan. These estimated benefits should nonetheless be viewed with caution, since none of the agricultural studies reviewed for this report account for the impacts of climate extremes (storms, flooding, drought) or changes in pests and disease on agricultural output and land values—they solely consider projected changes in mean variables.

Regarding forestry on the Prairies, climate change is projected to adversely impact timber supply leading to reduced sector output and value added (GDP). Results from one study suggest the present value of cumulative GDP for Alberta, Manitoba, Saskatchewan, Yukon and Northwest Territories over the period 2010-2080 could fall by $101.1B under a high climate, rapid growth, pessimistic scenario. Losses in Alberta were estimated at $21.3B. Climate change is also projected to increase annual fire suppression costs well above historic levels under a high emission scenario, with Alberta (+195% relative to historic levels) and Saskatchewan (+265% relative to historic levels) seeing significant increases in costs.

At the municipal level, two comprehensive analyses of the economic risks of climate change have been completed for the City of Calgary and the City of Edmonton. These analyses show that further climate change under the high emissions pathway RCP 8.5 is projected to result in total annual (tangible and intangible) losses for Calgary of $2.6B (2020 dollars) by 2055 and by $7.8B by 2085. For Edmonton, projected total annual losses amount to $3.3B (2020 dollars) by 2055 and $8.4B by 2085. These direct losses lead to secondary losses throughout the wider economy. The overall annual average impact on value-added (GDP) in the economy from the direct impacts of climate change on each city in 2055 and 2085 were estimated at, respectively, $2.2B (both Calgary and Edmonton) and $7.0B (Calgary) to $6.2B (Edmonton).

Before turning attention to current knowledge gaps, two observations from the studies reviewed are worth highlighting:

1. The first concerns the importance of future socioeconomic change (e.g., growth in populations, assets and wealth) as a determinant of the overall magnitude of projected economic costs. Notwithstanding its role as a key driver of estimated costs, socioeconomic futures are either incompletely addressed or not addressed at all in many studies.

2. The second concerns the importance of ensuring intangible climate-related costs are captured when measuring the costs of climate change. Intangible costs—in particular, those relating to welfare losses from impacts to public health—account for a sizeable share of estimated total costs.

10.2 Knowledge gaps

As part of the national climate change knowledge assessment, Boyd and Markandya (2021) concluded "*There is much that is yet to be known about the costs of climate change for Canada, both in aggregate and for specific sectors, regions, communities and vulnerable populations*." While our understanding of the costs of climate change for Canada and the Prairies has improved significantly since the national knowledge assessment was released—as the studies reviewed above show—there remains important gaps and limitations that should be borne in mind when interpreting the results:

- Infrastructure exists to produce service flows (e.g., drinking water, power, transport, housing, etc.) that residents and businesses on the Prairies value. With the exception of the time value of delays on transport infrastructure and the ecosystem services generated by natural areas and City trees in the City of Calgary and City of Edmonton studies, the dollar value of loss or disruption to services flows is not captured in the results presented above. This is despite the fact that numerous studies show individuals and businesses have positive willingness-to-pay to avoid disruption to services. Future investigations of the costs of climate change should incorporate forgone service flows from damaged assets and infrastructure.

- Most of the studies reviewed assess slow-onset climate impacts (i.e., ongoing changes in temperature and precipitation, and select biophysical impacts that result from these continuous changes). Only the analyses for the City of Calgary and City of Edmonton considered the economic consequences of acute, rapid-onset climate impacts, such as high winds, freezing precipitation, heavy snowfall, etc. This partly explains the relatively high projected costs for both cities. Future investigations of the costs of climate change should look to capture the projected impacts of extreme events and catastrophes (i.e., low-probability and high-consequence events)—in particular, climate extremes for agriculture where existing studies of slow-onset climate change suggest beneficial impacts for the sector. As illustrated in Section 3, the total economic consequences of weather extremes on the Prairies have been significant historically.

- Our understanding of the economic consequences of climate change for all key climate-sensitive sectors is incomplete. As the review above showed, a range of estimates have been produced for public health, transport and electricity T&D infrastructure, buildings, agriculture and forestry. However, gaps remain with respect to ecosystem services outside of the provisioning services provided by agriculture and forestry, primary extractive industries, water resources and tourism; future investigations of the costs of climate change could prioritize these sectors.

- Adaptation decisions are largely made at the local (municipal) level. Yet, comprehensive assessments of the costs of climate change to inform adaptation planning have only been completed for the City of Edmonton and City of Calgary[50]. Consideration could be given to undertaking similar studies for other key population centres across the Prairies.

- The available studies do not account for the potential of compounding or cascading effects. There are multiple ways that climate change can produce these effects. Compound effects occur, for example, when one set of climate impact-drivers result in multiple "impact chains" occurring simultaneously or in sequence, thus amplifying the overall economic consequences (e.g., the same climatic drivers that cause heat stress for workers and the general population can also cause drought and wildfire). When climate hazards occur in sequence (like the extreme heat and wildfires or the succession of "atmospheric rivers" that hit British Columbia in 2021) they act as a series of toppling dominos that accumulate and intensify, each becoming harder to manage as capacity to cope and recover becomes more strained, ultimately turning them into disasters with collective economic consequences greater than the sum of their parts. Cascading effects are indirect biophysical impacts of direct effects, such as when direct damages or losses to one system (like power outages from damage to electricity T&D infrastructure) from exposure to a climate impact-driver leads to spin-off impacts for other systems (like traffic signals, pumping stations, etc.). In the studies reviewed, climate impact-drivers are assessed as discrete events occurring in isolation in any given year. Future investigations of the costs of climate change should examine the multiplier effects of compounding and cascading effects.

- None of the studies reviewed for this report extend their analysis to account for feedback effects on projected growth. Simply put, they measure the impacts of climate change on the projected level of socioeconomic variables and not the underlying growth rate. Climate change can cause lasting damage to natural, manufactured and human capital and productivity in most affected systems and is thus likely to impact long-term growth rates underpinning the projections of socioeconomic change. As such, output and consumption at some future date will depend not solely on (say) the temperature at that date, but more so on the entire path of temperature, output and consumption up to that date. Studies that have investigated the impact of climate

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[50] A similar assessment has recently been completed for the Edmonton Metropolitan Region (the results have yet to be published), and others are soon to start for the MD of Pincher Creek, the Town of Devon and City of Lethbridge.

change on growth rates have found substantially larger losses than those that measured impacts on the projected annual level of output, due to the compounding effects of reduced growth[51].

Collectively, these knowledge gaps and limitations of current studies suggest the projected economic risks of climate change for the Prairies are almost certainly larger than the estimates presented in this report. To expand and refine the current state-of-knowledge regarding the costs of climate change for the Prairies, these gaps should be addressed. Finally, as noted in the Introduction, this information is used to inform the overall scale of investment in adaptation, and the selection, timing and sequencing of specific adaptation options, as well as the distribution of adaptation costs and benefits. It is suggested that a companion report be prepared to review the state-of-knowledge pertaining to the costs and benefits of adapting to climate change on the Prairies.

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[51] Boyd and Markandya (2021) ibid.

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