Climate Change in Canadian Agriculture:

The Context and the Evidence Demonstrate that Policy Should Refocus on Adaptation

AGRI-FOOD
ECONOMIC SYSTEMS

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Introduction

The specter of climate change haunts Canadian politics and economy, and with agriculture a significant proportion of Canada's total greenhouse gas emissions, it has become an important influence on agricultural policy. In agricultural policy discussions, the dimensions of conflict that relate to climate change are many and several. Agriculture in Canada is a significant emitter of greenhouse gases (GHG's- approximately 10 percent when on-farm heating is included); it is also a major sequesterer of carbon. Agriculture is largely exempt from carbon taxes; yet any carbon taxes paid (directly- as with grain drying or heating of farm buildings, or indirectly- such as through purchased inputs) presents the prospect of a cost competitiveness burden relative to Canada's competitors that do not have carbon taxes, and a source of sensitivity in the agricultural community. Even where carbon taxes are not applied, we have voluntary targets- such as on fertilizer GHG emissions, or the recently proposed methane protocol for livestock.

At the same time, governments with a progressive climate change agenda may feel that they cannot leave agriculture alone- it is simply too large a land use in Canada, and too significant an emitter. In this environment and on this issue, some farmers may feel singled out, unappreciated, or unjustly vilified.

However, the focus on effects of agricultural practices on climate change (and mitigating them) abstracts from the potential *impacts of climate change on agriculture* (and adapting to them). Food is increasingly scarce in the world, and Canada is a major net exporter of a broad range of farm and food products- among few others- and has relatively low carbon intensity in doing so. Global emissions reductions when demands for farm and food products are expanding thus depend on Canadian agricultural production, and that of other agri-food net exporters, to be sustained and grow under the challenges presented by climate change.

Understanding the imminent need for food in the world and challenges that will be presented by climate change in Canada, and what farmers will need to adapt to, frames the relative priorities of policies that facilitate adaptation relative to climate change mitigation. Thus, the lines of conflict between camps are now coming out in the open, and each attempts to position itself in the public debate on policies to mitigate climate change and strengthen global food security.

However, to understand the needs in policy, one first needs to know the science and the evidence.

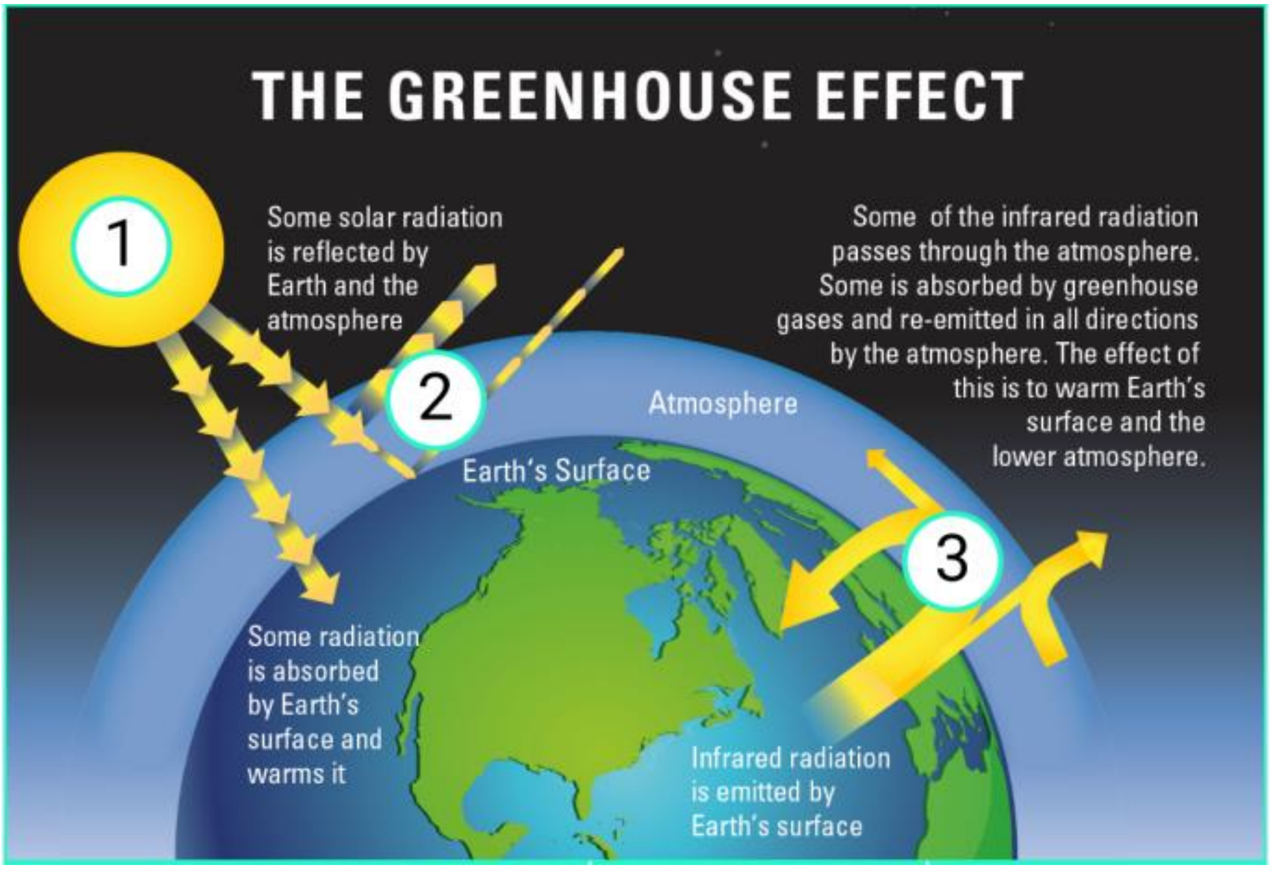
This paper explores (1) the nature of expected changes associated with climate that affect agriculture in Canada, (2) the evidence of changes to date and potential future changes, and (3) the challenges and opportunities that will exist for Canada, and apparent policy gaps. The paper concludes with how we should interpret the evidence and relative significance of policy for agriculture that facilitates adaptation to climate change and policy for mitigation of climate change.

Essential Mechanisms of Effect

Sunlight strikes the earth, and solar radiation is partially absorbed, and partially reflected back into space. The determinants of sunlight absorption and reflection are the earth's distance from the sun, the sun's temperature, and the rate at which the earth and the atmosphere surrounding it reflect the sun's rays. The earth's atmosphere distorts this relationship because the chemical compounds contained in the atmosphere influence the balance of absorption and reflection of solar energy. If the earth had no atmosphere, reflection would be much higher and the global average surface temperature would be -18°C (Hsiang and Kopp, 2018); the absorptive (or "greenhouse") effect of earth's atmosphere allows the balance of solar energy absorption and reflection to occur at a significantly warmer temperature- which, among other things, allows for agriculture.

The extent to which the earth reflects solar radiation is called the albedo effect; the effect of the atmospheric chemistry on increasing the earth's temperature is called radiative forcing. The dynamic of the atmosphere impacting the extent of solar radiation retention is summarized in Figure 1 below.

Figure 1



Source: Reprinted from Bush, E., Gillett, N., Watson, E., Fyfe, J., Vogel, F. and Swart, N. (2019): Understanding Observed Global Climate Change; Chapter 2 in Canada's Changing Climate Report, (ed.) E. Bush and D.S. Lemmen; Government of Canada, Ottawa, Ontario, p. 24–72.

Emissions of greenhouse gases have two important effects that relate to agriculture. First, the emissions contribute to radiative forcing by introducing additional GHG's into the atmosphere that alters the balance of absorption/reflection of solar energy toward greater absorption (increasing the greenhouse effect). Secondly, the emissions increase the concentration of atmospheric CO_2 which has complex effects on plant physiology and growth.

There are many complexities, nuances, and seeming contradictions to this dynamic. Initially, some forms of GHG emissions increase reflection of solar energy and actually cause cooling; as they later degrade they begin to absorb sunlight energy and contribute to the greenhouse effect (Hsiang and Kopp, 2018). Human activity can influence the albedo effect in reflecting solar radiation- Liu *et al.* (2021) found that adoption of no-till practices in western Canada had the effect of significantly increasing albedo, and that this had a greater effect on mitigating climate change than the carbon sequestration benefits associated with no-till. Cohen *et al.* (2021) showed that warming of the arctic can have the ironic effect of facilitating extreme cold events at temperate latitudes in North America and Europe due to the stretching of the stratospheric polar vortex. Pollack (2009) has found that melting sea ice due to climate change has the potential to interrupt and divert warm ocean currents, pressuring cooling in some regions such as northwest Europe.

Anticipated Effects

The warming that results from increased GHG emissions leads to greater absorption and retention of solar energy, and higher temperatures. The effect is illustrated in Figure 2 below, which plots annual global average temperature relative to the 1951-1980 index period. The data shows that at a global level, 2023 was the warmest in the dataset, and the upward trend is clear.

Warming has a diversity of climatic effects important to agriculture. Gornall *et al.* (2010) broke these effects down into direct climate effects- temperature and precipitation; variability in direct effects; and indirect effects. The literature dealing with these effects is immense; to make it palatable and provide a general indication, Canadian research reviews and systematic studies are scanned below.

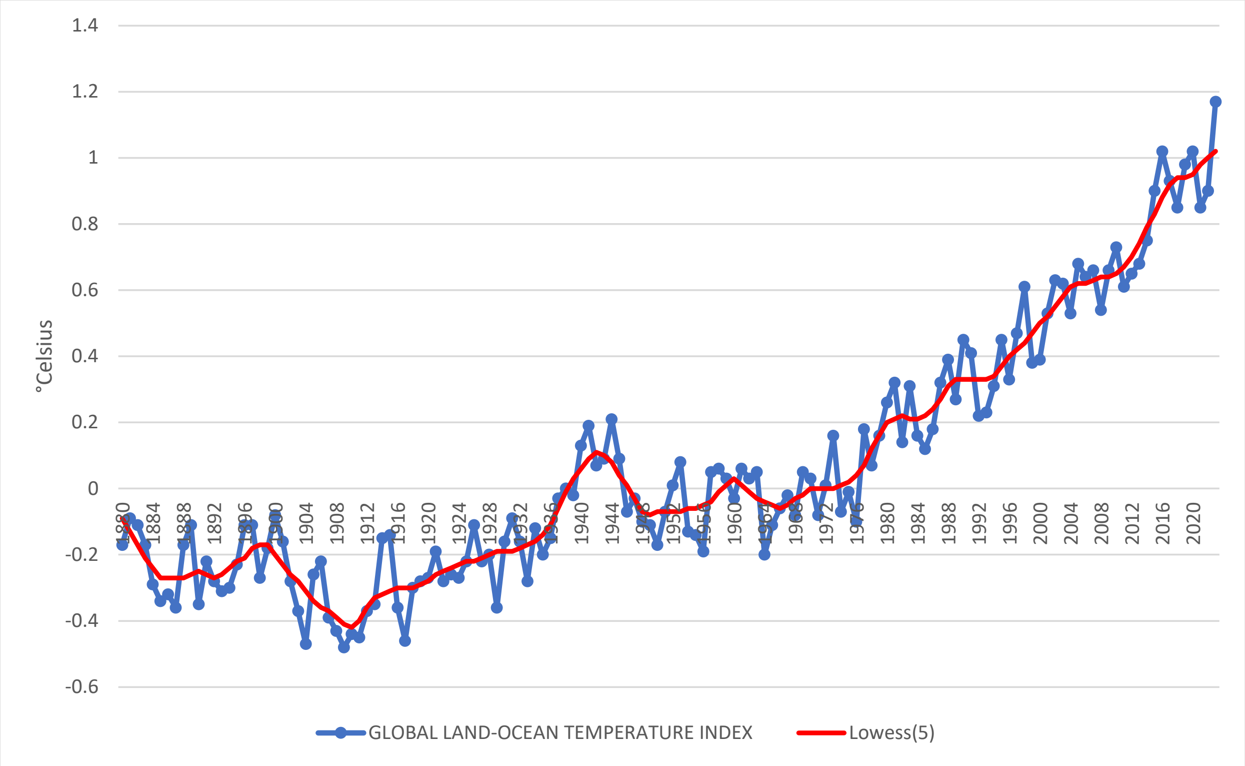
Direct Effects

1. Temperature

The most direct and obvious effect of global warming is increased temperatures. Temperature data ranges across space, seasonality, and mean vs daily high/daily low temperatures. Zhang *et al.* (2019) observed that mean temperature in Canada increased by about 1.7°C between 1948 and 2016, especially during the winter and especially in the northwest portion of the country. They also observed that "Summer warming was much weaker than that in winter and spring, but the magnitude of the warming was generally more uniform across the country than during other seasons."

In a recent review article, Mapfumo *et al.* (2023) observed broad increases in temperature in the Canadian prairie provinces; however, the effects observed were complex. In general, minimum temperatures increased more than mean or maximum values, and the largest proportional increases in temperature were in winter and spring. Increases were observed in both Growing Degree Days (GDD) and Effective Growing Degree Days (EGDD), with increases in GDD from

Figure 2 Annual Global Temperature Index, 1880-2023



Source: NASA's Goddard Institute for Space Studies (GISS). Index period is 1951-1980. Lowess smoothing based on 5 year intervals

1900-2002 of 10-12 percent observed in regions of Alberta. Increases in frost-free days were also observed throughout western Canada. Major *et al.* (2021) reviewed and updated corn heat units (CHU) for the Prairie provinces. They observed that, between 1920 to 2019, the Prairies had an average temperature increase of 1 to 4 ˚C over the last century due to warming in the winter months. They note that, “even though increasing winter temperatures have little impact on corn growth, an earlier start and later end of the season allows more time to accumulate CHU”. Ultimately, while “changes in summer air temperatures were minor, CHU has increased within the corn-growing area of the Prairie provinces by 200 to 400 during the past century”.

A study conducted for the Government of Ontario (Climate Risk Institute, 2023) also observed increases in temperature in Ontario between 1948 and 2012, most accelerated in the winter and in more northern regions of the province. A study of daily minimum temperatures and frost-free days in seven Ontario locations by Rudra *et al.* (2023) found that, between 1940 and 2010, daily minimum temperatures increased by well over 2°C, and that the number of frost-free days also increased markedly. Deen *et al.* (2021) observed an increase in mean temperature of .7°C between 1951 and 2013 at the Six Nations of the Grand in southern Ontario.

2. Precipitation

A warmer atmosphere has a greater capacity to hold moisture, potentially leading to increased precipitation and episodic heavy precipitation events (Hsiang and Kopp, 2018); however, the impact of global warming on regional precipitation is difficult to predict (Gornall *et al.*). This observation is borne out in Canadian data. Mapfumo *et al.* observed that "Canada's average total annual precipitation increased by 19 percent during the period 1948–2012. However, over the same period, decreasing trends occurred in southwest British Columbia, Alberta, and Saskatchewan." Zhang *et al.* (2019) observed that precipitation increase in Canada in 1948-2012 was larger in northern Canada, but that some areas in southern Canada, such as eastern Manitoba, western and southern Ontario, and Atlantic Canada, had experienced significant increases in precipitation over the period.

3. Extreme Heat

Vincent *et al.* (2018) observed a significant increase in the incidence of days exceeding 25°C averaged across Canada (on average, increased by almost 7 days between 1948 and 2016); this was robust in most regions, with the notable exception of the Prairies, and was not observed above 65° North latitude. Between 1948 and 2016, hot days (high temperatures exceeding 30°C) experienced an increasing trend in southern BC, southern Quebec, and the Maritimes, but experienced a decreasing trend in the Prairies. Over the same period, hot nights (low temperatures exceeding 22°C) only occurred in southern Manitoba, southern Ontario, and southern Quebec, and this experienced a significant increasing trend. Deen *et al.* (2021) observed an increasing trend in nights with lows exceeding 20°C and highs exceeding 25°C at Six Nations of the Grand in southern Ontario.

4. Drought

DeBeer *et al*. (2016) observed, based upon the literature on Western Canada, that "Since the beginning of the 20th century there has been decadal-scale variability in drought occurrence… but there has been no consistent long-term trend in drought frequency or magnitude". Bonsal *et al.* (2020) considered historic droughts in the Prairie provinces and assessed the risk of future droughts. Between 1900 and 2014, the most intense droughts (drought duration x intensity) occurred between 1910 and the late 1930's. However, when they applied a range of prospective future emissions scenarios to spatially fragmented data in multiple global climate models, their results suggested that "not only will there be more future severe droughts, they will develop more quickly, periods with extensive drought conditions will persist longer, and they will terminate more rapidly. These droughts will, therefore, be quite different from the 1917–1920 example… which had a more prolonged onset and termination."

5. Extreme Precipitation

Zhang *et al.* (2019) note that "there do not appear to be detectable trends in short-duration extreme precipitation in Canada for the country as a whole." Vincent *et al.* (2018) observed small increases in the rates of extreme rainfall regionally at locations in southern BC and also in eastern Canada since 1948.

Indirect Effects

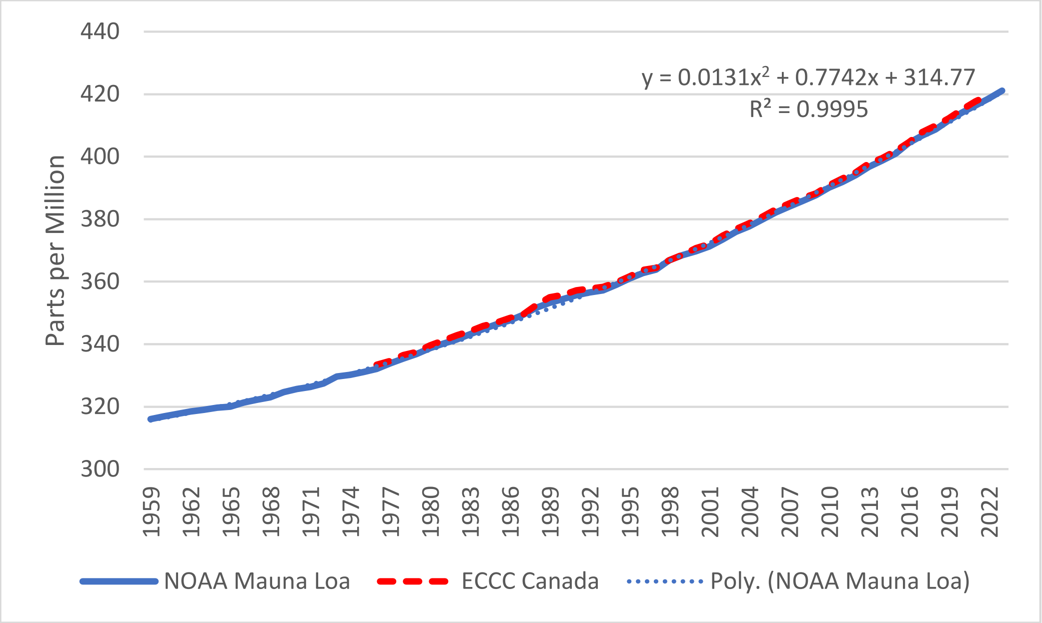
1. Increased Concentration of Atmospheric CO_2

Figure 3 below presents data on the atmospheric concentration of CO_2 in Canada since 1976, and from the National Oceanic and Atmospheric Administration collected in Hawaii since 1959. There appears very little difference between the two series where they overlap. In the mid-1970's, the CO_2 concentration was around 330 parts per million; since then it has increased to about 420 parts per million. The trend included in the figure indicates that atmospheric CO_2 concentration is increasing at an increasing rate over this time frame.

Most scenarios envision this concentration increasing significantly over time. This is illustrated in Figure 4 below, reprinted from the IPCC-AR6 Technical Summary. Most future scenarios envision global CO_2 concentration increasing to around 500 ppm, or potentially much higher, by 2100.

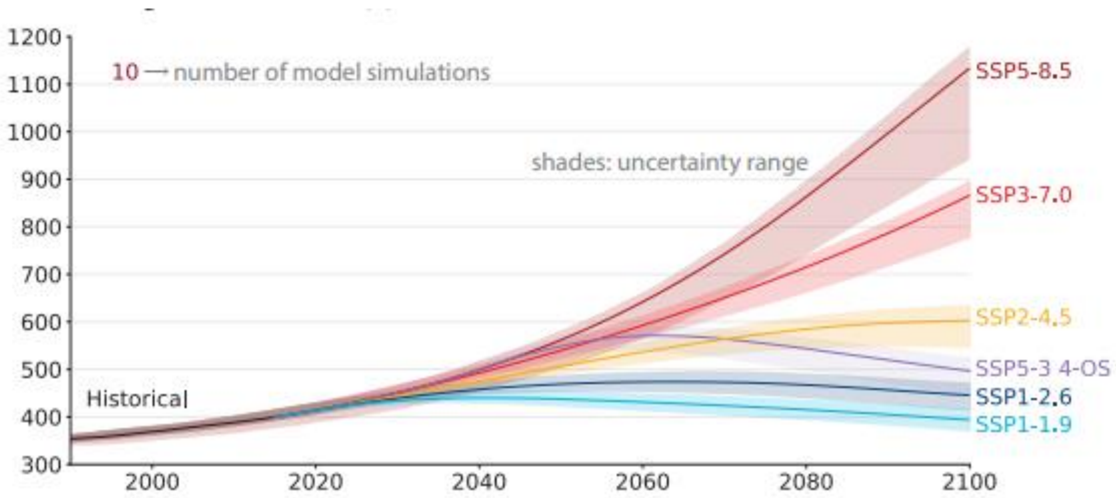
Increasing atmospheric CO_2 concentrations have important effects on plant physiology. Gornall *et al.* (2010) describe this as CO_2 fertilization, that varies across plant species according to photosynthetic pathways- crops with a C3 pathway include most cereals, oilseeds, fruits and vegetables; tropical grasses- including corn, sorghum, and sugarcane- have a C4 pathway. Crops with a C3 pathway can significantly increase photosynthesis under elevated CO_2 concentrations; for C4 crops elevated CO_2 concentrations have much less effect.

Figure 3 Carbon dioxide concentration, 1959 to 2023



Sources: (1) Dr. Xin Lan, NOAA/GML (gml.noaa.gov/ccgg/trends/) and Dr. Ralph Keeling, Scripps Institution of Oceanography (scrippsco2.ucsd.edu/)
(2) Environment and Climate Change Canada (2023) Climate Research Division, Canadian Greenhouse Gas Measurement Program. From 1976 to 1999, averages were calculated based on data from 2 to 3 sampling stations. Since 1999, data from 5 sampling stations are used to represent CO2 concentrations.

Figure 4 Prospective Future Concentrations of CO_2 (ppm) Estimated in IPCC AR6



SSP: Shared Socio-economic Pathway scenario. SSP5-8.5 is the highest CO_2 emissions scenario, and SSP1-1.9 represents the low end of future emissions pathways

Source: reprinted from *Technical Summary. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*

Studies observed by Gornall *et al.* found that, relative to baseline yields, at CO_2 concentrations increased to 550 ppm, yields of C3 crops increased 10-20 percent, and C4 crops had yield increases of 0-10 percent. Kimball (2016) reviewed studies employing free-air CO_2 enrichment (FACE) technology. Observed yield changes under ample nitrogen and moisture conditions at CO_2 concentrations raised to around 550 ppm averaged 19 percent for wheat, rice, and barley, but with much higher yield responses in hybrid rice. Soybeans were observed to have a 16 percent higher yield under CO_2 fertilization. In contrast, the yield response of grain corn and sorghum was negative.

Qian *et al.* (2019) assessed the effects of warming at varying levels on Canadian spring wheat, canola, and corn yields using a range of 20 global climate models and 3 crop growth simulation models with a spatially disaggregated dataset. They observed a robust finding, across crop models, of wheat yields increasing with warming level- entirely caused by corresponding increases in atmospheric CO_2 concentration (otherwise wheat yields would fall with warming). One crop model generated a 22 percent increase in wheat yield with warming of 3°C. Similar findings occurred with canola although there was less agreement among crop models. The results showed that increased atmospheric CO_2 concentration had a negative impact on corn yields.

There is evidence that increased atmospheric CO_2 concentration has physiological effects on crops extending beyond yield, and impacting the nutrient and chemical makeup of the crop itself.

Myers *et al*. (2014) compared the nutrient content of crops at multiple global locations at existing and elevated levels of atmospheric CO_2 concentration in a meta-analysis of studies. They observed the effects of experiments in which crops experienced elevated CO_2 concentrations of 546-584 ppm. The results are summarized in Table 1 below. With regard to protein, the C3

Table 1 Observations of Significant Nutrient Changes Under Elevated CO_2 concentration

	Photosynthetic Pathway	Protein	Zinc	Iron
Wheat	C3	Lower	Lower	Lower
Barley	C3	Lower	Lower	Lower
Rice	C3	Lower	Lower	Lower
Corn	C4	No Change	No Change	Lower
Sorghum	C4	No Change	No Change	No Change
Soybean	C3	No Change	Lower	Lower
Field Peas	C3	Slightly Lower	Lower	Lower
Potato	C3	Lower	No Change	No Change

Source: Summarized from Myers *et al.*, 2014

crops generally had a significant reduction in protein level under elevated CO_2, with soybeans and field peas important exceptions; the C4 crops listed (corn, sorghum) experienced no change. Levels of zinc and iron followed a similar pattern for C3 vs C4, but with potato exhibiting no change, and corn having decreased iron content.

Jin *et al*. (2019) considered the effect of elevated atmospheric CO_2 concentration on the nutrient content of selected field crops in a long-term study that considered the effect of soil types. They observed that, in a wheat-field pea-canola rotation, regardless of soil type, at atmospheric CO_2 concentrations around 550 ppm, the concentrations of nitrogen, phosphorus, and zinc decreased significantly- across crops. The largest decreases in N were observed in wheat and canola. They concluded that elevated atmospheric CO_2 concentration "lowers the nutritional quality (nutrient concentration) in grains of non-legume crops, and that the extent of this decrease was greater in relatively fertile than infertile soils".

Doddrell *et al.* (2023) reviewed the evidence on elevated CO_2 concentration in greenhouse environments on vegetables and fruit. They found that in greenhouse environments with CO_2 concentrations supplemented up to 2000 ppm, across a range for vegetables (tomato, pepper, cucumber) and some fruits (strawberry, raspberry, cherry) elevated CO_2 concentration generally increased sugars and mostly increased nutrient values.

Elevated CO_2 concentration also has the effect of enhancing water use efficiency in plants, defined as the biomass growth per unit of water used by a plant. Hatfield and Dold (2019) reviewed studies examining water use efficiency under elevated CO_2 concentration, and found a broadly beneficial effect on C3 plants. Little effect was observed in C4 plants when water was not a limiting factor; however, a beneficial effect was observed under conditions in which water is a limiting factor due to reduced stomatal conductance. The corollary is that, where elevated CO_2 concentration does not increase photosynthesis and yield, the crop uses less water.

Another aspect of crop physiological effect from elevated CO_2 concentration relates to seed vigour. Hampton *et al.* (2013) conducted a review of seed quality under elevated CO_2 concentration. They observed that, "predicted environmental changes will lead to the increased occurrence of loss of seed quality, particularly seed vigour and possibly germination. While seed mass will also change, this does not necessarily imply any negative effect on germination or vigour." Lamichaney and Maity (2021) reviewed the implications of elevated atmospheric CO_2 concentration on various aspects of seed quality- seed weight, germination, vigour and biochemical constituents. They observed no consistent effect from elevated CO_2 concentration on seed weight; many crops exhibited no effect or an increase in germination performance, with reduced germination for chickpea and rice at high concentrations of atmospheric CO_2. Seed vigour was observed to be typically compromised under elevated CO_2 concentration, and the carbon:nitrogen ratio and a range of chemical changes in seeds were observed.

Increased Spread of Disease and Pests

Bebber (2015) observed that "species ranges should shift in response to changing climate, as the geographic region with a climate suitable for population growth is altered. As a first approximation, global warming leads to a poleward shift in isotherms, which populations should track, and observed changes in the distributions of wild species have been cited as among the strongest evidence for the biological impact of climate change"; however, this approximation is complicated by a variety of factors such as oceans, landforms, the spatial dynamics of climate change- and the role of trade and human travel in spreading pests and pestilence. In a more recent review focusing on plant pathogens, Raza and Bebber (2023) reviewed observational studies, mechanistic studies, and experimental work. They observed evidence that, in China, climate change, particularly warming nights and reduced frosts, accounted for one fifth of the observed rise in pest and disease occurrence. Other studies have shown that the spread of soil fungal diseases is strongly influenced by temperature, followed by precipitation. Fungal and oomycete diseases are positively correlated with crop yields under global warming.

Boland *et al.* (2004) provided an assessment of the effect of climate change on crop diseases in Ontario. They evaluated survival of primary inoculum of the pathogen, rate of disease progress during a growing season, and the duration of the annual epidemic for fungal diseases, bacterial diseases, viral diseases, nematodes, phytoplasmas, and abiotic diseases. The authors assumed that the future Ontario climate will be warmer and drier- which will generally promote over winter survival of diseases, have a mostly negative impact on disease progress in the growing season, but promote the growth of soil borne pathogens. The prospect of changes to invasive foreign plant diseases under climate change was not evaluated.

Observations

The evidence above presents a complex mixture of conditions that Canadian agriculture should expect to confront. Some elements are relatively certain, although the long-term climate datasets drawn upon generally end in 2016, omitting some notable recent climate events.[1]

- Temperatures in Canada are warming. However, this is disproportionately occurring in winter, and in northern regions. Temperatures have mostly not increased on the Prairies.

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[1] Such as the "Harvest from Hell" (2019); western Canadian drought- widespread in 2021, and regional/localized since; local extreme heat in southern BC and heat dome event (2021) and extreme heat and wildfires in 2023; extreme rainfall and flooding in lower mainland of BC and parts of the maritime provinces (2021)

Nonetheless, there are broad increases across the country in growing degree days, corn heat units are increasing, and the growing season itself is becoming longer

- Precipitation has increased, particularly in the north, and in selected agricultural regions- parts of Manitoba, southern Ontario, and the Maritimes. However, precipitation has not increased in southern BC and in most of the Prairie provinces
- Extreme heat events are increasing regionally, but this appears not to be occurring in the Prairies
- Droughts do not appear to be increasing in frequency or intensity, acknowledging that the most recent data is excluded in reaching this conclusion. There is evidence suggesting that droughts will become more frequent and develop more quickly in the future
- Extreme precipitation does not appear to be increasing in frequency or intensity, acknowledging that the most recent data is excluded in reaching this conclusion
- The atmospheric CO_2 concentration has been increasing, recently at about 420 ppm, up from less than 320 ppm in the early 1960's. Based on a range of global scenarios and forecasts, it is reasonable to expect that this level will approach or exceed 500 ppm prior to the year 2100, and could be much higher than 500 ppm by that time.
- The increase atmospheric CO_2 concentration increases the yields of C3 crops markedly when provided with adequate moisture and fertility. At atmospheric CO_2 concentrations of 550 ppm, it is reasonable to expect yield increases in major cereals in Canada will increase up to 20 percent in relation to past experience with CO_2 concentration in the low 400's ppm. However, this will have negligible yield effect for grain corn.
- The increased atmospheric CO_2 concentration impacts the content of critical nutrients in C3 grains and oilseeds. Protein levels are significantly reduced- but not for soybeans, and only marginally for other legumes- and levels of zinc and iron are more generally reduced. Increased atmospheric CO_2 concentration, at least at levels applied in greenhouses, seems to increase the content of most nutrients. Again, grain corn is largely unaffected, with the exception of iron.
- Increased atmospheric CO_2 concentration will alter the chemical composition of seeds, likely impairing seed vitality.
- Global warming will expand the reach of pests and disease, on the basis of higher temperatures, higher precipitation, and increased crop growth. We should expect further northward movement of foreign pests and disease into Canada and increased incidence and severity of existing pests and disease.

While the focus here is on Canadian agriculture, some of the above effects carry important global impacts. The world is certainly warming, and in many parts of the world, warmer will also be drier, which places downward pressure on crop yields, despite the beneficial effect of CO_2 fertilization. The prospect of diminished seed vigour builds on worries of yield losses. Increased atmospheric CO_2 concentration and changes in crop nutrient profiles also present the prospect of important dietary deficiencies in already food insecure parts of the world. In turn, this places further pressure on the agricultural production systems of net exporting countries like Canada to fill in the gaps.

Canada is getting warmer and wetter, to varying degrees, and this has important agricultural implications for a northern climate. It is resulting in a longer growing season, and more heat, supported by adequate precipitation- a recipe for increased yields, movement of crops into areas in which the climate has previously been unsuitable, and a movement of agriculture into regions with climates that have previously been unsuitable to be farmed.

But there are concomitant risks. Not all regions, and importantly not much of the Prairies, have seen these effects. Indeed, if public support for climate change mitigation initiatives is relatively low in the Prairies, it may be because the Prairies perceive little in terms of the real effects of climate change. At the same time, there is an expectation that in the future, droughts will be more frequent and develop more quickly in the West. Elsewhere, the country has gotten warmer and wetter, contrary to the expectations laid out by Boland *et al.* What this means is that, as pests and diseases move north with increasing temperature, they will not be greeted by a drier climate- it is a wetter one, probably exacerbating the effects of existing and foreign crop diseases. Canada will be subject to the global crop physiology effects of the increasing atmospheric CO_2 concentration.

Beyond the sobering challenges these observations carry, there are important implications in terms of how we understand contemporary agricultural progress, returns to research, and productivity growth relative to the CO_2 fertilization effect. This appears not to be widely recognized.

To illustrate, Qi *et al.* (2019) report results on projected Canadian yields of spring wheat, canola and grain corn at atmospheric CO_2 concentrations associated with discrete and well identified warming scenarios, and also report yield results with atmospheric CO_2 concentration standardized at 380 ppm. The differences are stark; significant yield increases are observed for all crops under warming scenarios with CO_2 fertilization, but projected yields *decrease* under warming when CO_2 concentration is held constant. Other studies of the agricultural effects of climate change omit the effect of increased atmospheric CO_2 concentration. For example, Ortiz-Bobea *et al.* (2019) assessed the key climatic drivers of yields in major US field crops, using many of the same global climate models as Qi *et al.*, with some focus on the impact of increased temperature and decreased soil moisture. They find that climate change increases temperatures and heat stress, reducing soil moisture, and reducing US crop yields- ignoring the effect of CO_2 fertilization that could have more than an offsetting effect.

Total Factor Productivity (TFP), and more specifically the rate of change in TFP, is a commonly used metric of the rate at which productivity in agriculture is changing. It is estimated by taking a measure of output (e.g. agricultural production), accounting for the measurable inputs associated with it (e.g. land, fertilizer, seed, pesticides, irrigation, etc.), and then observing the residual of output not explained by measurable inputs. This residual component is TFP, and it is a barometer for the value of improvements in unmeasurable inputs like genetics, managerial performance, data capture-transfer-implementation, etc. If the CO_2 fertilization effect is not accounted for as measurable input, it is implicitly lumped in with TFP. The result is that the TFP measure becomes inflated, and makes it appear that aspects like TFP due to research and innovation are actually contributing more to productivity than they really are- a form of omitted variable bias.

This could change the interpretation of observed changes in TFP. To illustrate, Ortiz-Bobea *et al.* (2021) considered the impact of anthropogenic climate change on TFP in agriculture from 1961 to 2020. They found that the global index of agricultural TFP increased 76 percent between 1961-2015; however, it would have been far higher, but for anthropogenic climate change. By isolating anthropogenic climate change and estimating the effect of growing season temperature and precipitation on TFP, their results show that anthropogenic climate change has reduced global TFP by 22 percent. However, their data and findings omit the effect of increased atmospheric CO_2 concentration. So the analysis accounts for the negative impacts of climate change (hotter and drier) but not the positive impacts (CO_2 fertilization). We are left to speculate as to the true net effect.

With the CO_2 fertilization effect on C3 crops demonstrated as significantly increasing yields in many studies, surely this aspect of climate change elevates current TFP calculations in agriculture. When this is properly acknowledged, it is possible that increased atmospheric CO_2 concentration has been holding up estimated TFP at observed levels, and that the components most closely associated with TFP- improvements in genetics, improvement in management, etc. have actually been exaggerated in their significance. Moreover, especially in a northern climate such as Canada, it is quite possible that estimated TFP in agriculture has experienced a net benefit from climate change.

Observed Global Effects

Mirzabaev *et al.* 2023 observed “Climate change will affect food systems differentially across world regions. While some areas, such as northern temperate regions, may even experience some beneficial changes in the short term, tropical and sub-tropical regions worldwide are expected to face changes that are detrimental to food systems.”; and “In temperate climatic zones, such as northern China, parts of Russia, northern Europe, and parts of Canada, observed climatic changes are increasing the agricultural potentials, leading to higher crop production.

The evidence of agricultural effects associated with climate change is building. Some of this is associated with episodic extreme weather; for example, Qamer *et al.* (2023) estimated production losses due to historic monsoon rainfall and devastating floods in Sindh province Pakistan in 2022 of 80 percent for rice, 88 percent for cotton, and 61 percent for sugarcane. Assessing the more systemic effects on global agricultural systems is more difficult, given year to year variation, established yield trends, differences in farm management, and sub-national spatial variation. Ray *et al.* (2018) developed an empirical model of global crop yields and climate variables with 20,000 spatial political units represented for ten crops- barley, cassava, corn, oil palm, rapeseed, rice, sorghum, soybean, sugarcane, and wheat- for the period 1974-2008. The global results are summarized in Table 2 below. Across crops, the table shows broad decreases in yield for C3 crops, with notable exceptions- particularly soybean, while several C4 crops experienced yield increases- notably sorghum and sugarcane. However, on balance, the global yield of staple crops has experienced important negative effects, especially on food grains (wheat and rice). As should be expected, there is great variation across regions- among the most adversely impacted are West, South, and Southeast Asia; Western and Southern Europe; and sub-Saharan Africa. For the vast majority of crops and regions, these estimated yield changes reflect the preponderance of acreage.

Table 2 Estimated Percentage Changes in Global Yield Associated with Climate Change, 1974-2008

	Barley	Cassava	Corn	Oil Palm	Rapeseed	Rice	Sorghum	Soybean	Sugarcane	Wheat
North and Central America	-2.5	-2.9	0.5	-7.2	-0.4	-0.1	4.3	3.3	1.7	-1.3
Caribbean and South America	4	0.5	2.7	-0.6	6.8	-0.7	0	5.4	2.5	-1.6
Western and Southern Europe	-16.1	NA	-0.63	NA	-11.4	-3.2	-18.2	-21.2	2.7	-8.7
Eastern and Northern Europe	-9.1	NA	-24.5	NA	3.1	-0.04	-9.5	-3.8	NA	-2.1
North Africa	-6.8	18	-4.3	NA	NA	-1.3	17.9	10.9	-5.1	12
Sub-Saharan Africa	-0.6	1.7	-5.8	0	24.9	-3.1	0.7	-1.6	-3.9	-2.3
Central and Eastern Asia	1.6	1.2	5.1	-0.4	5.9	0.9	4.9	0.2	5.3	4.5
West, South, and Southeast Asia	-0.9	-5.6	1	-15.9	1.9	-0.8	0.9	-3.2	-0.6	-0.9
Oceania	-2.3	NA	-1.2	NA	0.6	4.1	-30.5	-6.3	0.4	-5.8
Global	-7.9	-0.05	0	-13.4	0.05	-0.03	2.1	3.5	1	-0.9

Source: Reprinted from Ray *et al.* (2019). NA= Not Applicable

Policy Implications

Agriculture and food presents a unique situation relative to climate change, and for climate change policy. Agriculture and food production represents a significant proportion of global anthropometric GHG emissions; this is also the case in Canada. The magnitude of emissions from agri-food makes it a target for emissions mitigation. Agriculture is also acutely sensitive to climate change and changes in weather patterns, extreme weather, etc. whereas most other segments of the economy are much less affected. Efforts to mitigate climate change through agriculture thus present the prospect of reducing yields and agricultural production, and undermining food security; this is especially a concern for an agri-food net exporter with an agricultural system broadly advantaged by climate change.

This general dilemma between climate change mitigation and adaptation is receiving some attention. In a recent book, Sutton *et al.* (2024) observe that the Paris Agreement targets cannot be met without the global agri-food sector achieving net-zero emissions. They present the prospect of a vicious cycle- in which climate change erodes crop yields, additional land is forced into production generating a GHG emissions increase, causing additional climate change- in a recurring cycle. However, they also acknowledge that poorly designed policy reforms could have the effect of lowering agricultural production, and increasing global food prices. Hasegawa *et al.* (2018) investigated the tradeoff between global climate change mitigation policies and food security. Using an ensemble of models dealing with climate change, efficacy of mitigation, agricultural commodity prices, and food security, they found that the most stringent climate change policies enacted on a global, economy-wide basis would "have a greater negative impact on global hunger and food consumption than the direct impacts of climate change". How climate change policy is structured for agriculture is thus very important and indeed determinant.

The problem facing Canada is somewhat unique in this regard. As shown in Table 2 and elsewhere, Canada does not face Sutton *et al.'s* "vicious circle" as do most other countries, because the changes in the Canadian climate stand to be beneficial for its agriculture (at least for now). Moreover, Canada is a significant net agri-food exporter with capacity to help offset reductions in food production elsewhere in the world due to the detrimental effects of climate change on agriculture.

A working paper by Nath (2020) puts the problem in sharp relief- and highlights a different risk for agri-food net exporters like Canada. He observes that manufacturing industries are much less impacted by climate change than agriculture- so countries with agricultures that are advantaged by climate change should specialize in agri-food production and export to the countries closer to the equator with agricultural systems adversely impacted by climate change. But many of the countries facing food security challenges from climate change are less developed countries with high proportions of employment in agriculture, that place a high value on self-sufficiency, and could be inclined to use protectionist trade policy to protect the domestic workforce and safeguard (withering) food subsistence. Nath concludes "Policymakers often prioritize "food security" as a stated aim, implying a preference for domestic food production secure from interference by foreign countries. To the extent that this goal conflicts with adaptation to climate change in light of large declines in agricultural productivity in certain regions, it may be worth examining this trade off." Moreover, protectionist trade policies enacted by countries struggling to maintain their food security based on domestic production could serve to undermine adaptation policies pursued by countries that are agri-food net exporters, with agricultural systems that are advantaged by climate change.

What should we assume about global agri-food trade policy as climate change weakens the food security status of countries becoming warmer and drier, even if it advantages others like Canada? Will it drive a return to more of an open, rules-based trading system in which countries with agri-food surpluses to export will have reliable access to markets that need to import, regardless of their economic weight, and can reliably invest in capacity accordingly? Or, conversely, will it give way to a more fragmented system driven by food geopolitics, in which importers respond to eroding food security through public stockholding, protection, and subsidy to expand less efficient (and higher emitting) domestic agri-food production systems, increasingly struggling with the effects of climate change? Canada has pursued the case for renewal of rules-based trade through the Ottawa Group and in various elements of the WTO; but Canada should also have a strategy for agri-food trade under fragmentation if this effort fails.

What we know about the performance of investments in productivity improvements appears also to be in question, given that the CO_2 fertilization effect has received less attention in measurements of TFP and returns to agricultural research. One explanation for this is that it relates to uncertainty regarding the extrapolation of experimental work on CO_2 fertilization to the broader context and mass acreages globally. Surely this can be validation tested, with new work utilizing the results in improved estimates of agricultural TFP and TFP growth rate. This is a crucial issue, as it offers the prospect that true TFP growth based on agricultural innovations has actually been much lower or slower than previously believed, entailing a redoubling of efforts in agricultural research and development.

The Canadian data suggest that climate change experienced to date spans a wide bandwidth- warmer- but mostly in winter and mostly in the north, and not much at all on the Prairies; wetter- but mostly not in the west; with recent experience of climate extremes, but no apparent trend in that regard over time. Future projections- which entail a range of warming from not much different from the *status quo*, to rather extreme and dire- generally reinforce existing trends, with a sense that Prairie drought could occur more suddenly and become more common.

Canadian agricultural policies must thus recognize that climate change is perceived differently across regions of the country, and that farmers will need to be equipped differently to respond and adapt accordingly. The politics of the situation are complicated by the fact that Canada's major agricultural production region has thus far been impacted minimally by climate change. This suggests that a single national approach will find less traction than one that is flexible to the needs of provinces/territories and local areas, and one that allows for program funding to target issues on a disaggregated basis. For example, policies that help farmers address the problem of very warm overnight lows in summer and prospective yield/quality loss will be more much more impactful in Ontario, Quebec, and the BC lower mainland than they will in Saskatchewan; the converse is true of drought preparedness/mitigation.

There are broad demands that will confront agricultural research. Kulshreshtha and Wheaton (2013) draw attention to the problem of knowledge gaps regarding climate change adaptation- dealing with events and impacts that have not occurred in a very long time (e.g. long-term drought in western Canada), or have never occurred (e.g. agricultural development north of 60° latitude).

There will be a demand for more refined and detailed understanding and interpretation of evolving weather patterns, at a localized level. This will need to inform what we should expect regarding windows of time and weather patterns for specific farming operations- for example, the number of consecutive days of dry weather that can be expected seasonally for hay to dry in the field, or the expected rain-free seasonal window for fertilizer/pesticide applications. Historical records are often available at a local level, but understanding and projecting changes can guide adaptation, such as the use of hay drying amendments (e.g., acids; bacterial cultures) or enhanced nitrogen fertilizers, and identify needs for new solutions through research and innovation.

A related problem is episodic weather events and infrastructure. Local average precipitation may not change, but if the climate evolves such that it becomes more concentrated seasonally, or in fewer precipitation events within a season, it can both weaken existing infrastructure and require additional infrastructure. For example, less frequent but heavier rains may require higher capacity sloughs or water retention ponds, and weaken public infrastructure reliant upon by agriculture, like rural roads, bridges, public irrigation projects, etc.

More specific research priorities will include new tools to counter increased pressure from pests and diseases, new varieties/cultivars developed for the changing climate and resistant to the emerging pests and diseases, and a proactive system that can expedite product registrations and approvals. As a northern country, there will be an advantage to utilizing/adapting existing varieties from warmer regions where the emerging pests and diseases already exist. This underscores the importance to Canada of heavy involvement in international agricultural research collaborations, such as the Consultative Group on International Agricultural Research (CGIAR). Unintended consequences of adaptation, such as potential for threats to biodiversity as agriculture in Canada moves north, requires work to understand mitigation and harm avoidance.

Conclusion

Changes in the climate entail a complex set of important disruptions for the global agri-food system. These changes present important opportunities for Canada as a country capable of producing large surpluses of farm and food products relative to its domestic needs, and observing some agricultural benefits from climate change. Elsewhere, climate change is menacing food security where a warmer and drier climate drags down agricultural production, and food security was already in a tenuous balance. In this context, Canada can play a role as an agri-food exporter among few others.

For Canada, surely climate change mitigation is less important than adaptation to climate change- given the magnitude of observed and expected changes, and because food is a fundamental, imminent, need that is highly sensitive to climatic conditions, and that is scarce in the world. Consumption of other types of products in the economy- non-food goods and services- can be traded off far more easily in reducing GHG emissions than can food. Imagining a world in which the climate evolved to be less hospitable to farming, and in which we were unprepared for it, presents an acute crisis and a troubling prospect.

Climate change mitigation is a much longer game. Ultimately, successful mitigation will be a substitute for adaptation- but this depends on mitigation efforts that are genuinely successful, on global efforts (not just Canada's efforts), and will take decades. We need to achieve and sustain food security in the world to buy this time.

Even if Canada appears to be a beneficiary of climate change in consideration of agriculture (at least for now), areas closer to the equator that represent the preponderance of global population becoming warmer, drier, and more subject to climate extremes, and face the prospect of serious threats to their food security and dietary deficiencies. In this environment, farmers in Canada will need the resources and flexibility to adapt in order to sustain and expand agricultural production for domestic economic development, and to contribute to food security elsewhere. This implies a clear priority on adaptation. Policies that can both facilitate adaptation and mitigate climate change will be ideal- and these should be clearly identified- but mitigation cannot have a priority over adaptation, nor should adaptation be materially traded off for mitigation. It is a situation that Canadian agri-food policy has not faced previously.

Canadian agriculture needs the tools to adjust to climate change, and there are there are many challenges- technical challenges, such as new pest and disease pressures- also policy challenges that reflect the range of experience with climate change thus far, many uncertainties, and differential needs relative to adjustment across regions of the country.

The awareness of the significance and priority on climate change adaptation could offer a reset on the climate policy discussion in Canada, currently dominated by mitigation. Mitigation is an important, long-term proposition, and Canada is playing a lead role. Adaptation anticipates an acute and overwhelming risk to the agri-food supply. As such, opportunities for mitigation in agriculture should be focused where there is overlap with adaptation strategies and search for synergies, rather than leading with policies focused on mitigation at the exclusion of adaptation. A public policy discussion based on the understanding of changes in climate, opportunities, and needs for adaptation in agriculture, with mitigation as a subset, is a more enabling and unifying one.

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