

A call for action to improve Canada's food security in the face of climate change

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1. Summary

Climate change threatens Canadian society through the growing risk it poses to national and global food security. We've begun to see localized crop failures both domestically and around the world that remind us the risk of famine is not exclusively a historical problem nor a problem that will only affect developing nations. Existing "action" plans endorse the need to improve Canadian food security (Government of Canada 2016, 2018), but lack *implementation* plans that could produce the desired actions. We've learned from Canada's Covid-19 response that having an action plan doesn't help if we don't have an implementation plan that makes the action plan a "living" document that is part of daily government operations (Hart 2021); in response to the SARS Cov-2 and Middle East Respiratory Syndrome (MERS) outbreaks (in 2003 and 2012, respectively), detailed plans were prepared, and then promptly forgotten.

Although Agriculture Canada has drafted an "Emergency Management Framework for Agriculture in Canada" (<https://agriculture.canada.ca/en/canadas-agriculture-sectors/animal-industry/agriculture-emergency-management/emergency-management-framework-agriculture-canada>), this document has two notable problems: First, it includes a list of deliverables without identifying specific actors (e.g., the position of "Deputy Minister" or the name of an officeholder) who will be responsible for each deliverable. Second, there are no dates by which the deliverables must be completed (Annex 4 of the federal framework). Phrases such as "explore creation of information sharing and communication networks" sound laudable, but less so than "establish information sharing and communication networks that include federal and provincial Agriculture ADMs by August 2021". As such, the framework is an "inaction plan". (I have written repeatedly to the Department of Agriculture to request copies of the annual report and any action plans developed under the framework, but have received no reply.)

In this white paper, I will focus on the framework's deficiencies rather than on the parts that seem to have been covered. For example, I saw no recommendation that governments study and implement the required logistical support for large-scale food storage to ensure that food will remain available in the event of widespread crop failure.

Note: I have not considered the "Agricultural Climate Solutions" program (<https://agriculture.canada.ca/en/agriculture-and-environment/agricultural-climate-solutions>) in this white paper, since that program refers to combating climate change rather than to improving food security.

Given the magnitude of the risk posed by climate change and the difficulty predicting when that risk will manifest, we must begin developing and testing implementation plans that will be economically efficient now, and that can be scaled up rapidly and implemented nationally if a food shortage develops. It's worth noting that one reason Newfoundland responded successfully to the influx of grounded airplanes after the 9/11 terrorist attacks was because they not only had a plan in place; they also tested and revised the plan (<https://www.cbc.ca/news/canada/newfoundland-labrador/gander-emergency-management-1.6164287>). Adopting Newfoundland's approach will have several advantages:

- It will minimize the cost, since implementation can be performed proactively and spread over time, rather than becoming a crisis response concentrated within a short period. As the Covid-19 pandemic response clearly demonstrated, reactive plans are far less effective than proactive plans.
- Small-scale implementation will allow testing of solutions to ensure they work and are economical before expanding them to a national scale.
- Gradual implementation will produce minimal disruption of the lives of Canadians, and will thus encourage cooperation and participation.

My university training is in ecosystem science with a specialization in plant physiology and genetics. For more than 35 years, I've worked with scientists from around the world who study climate change and the agricultural and political responses required to confront this problem. I've read and helped scientists to publish (literally) thousands of peer-reviewed science journal papers on climate change and the plant and ecosystem responses. Based on this research, I believe that climate change threatens Canadian lives through crop failures—something that seemed unimaginable until recently. Canada may be spared the worst impacts, but we won't escape unscathed. We need to act now to minimize the consequences.

Note: Because my primary expertise relates to plants, and because agricultural animals depend on plant matter, I will focus on plants in this white paper. There will be parallel problems and parallel solutions required for animal agriculture. For example, a severe shortage of fodder created significant problems in 2021 and 2022 for cattle farmers.

In section 2, I will describe the main problems. In section 3, I will describe potential solutions. In section 4, I will conclude with a call for action. This will not be an exhaustive analysis, but rather one intended to raise awareness of the key points and motivate action.

Note: Since I don't know who will read this white paper, I've provided a simple and clear description, supported by evidence (literature citations in brackets). I've also chosen simple examples rather than performing an exhaustive literature review. If you already understand these issues, skip ahead to section 3.

2. Description of problems

The Covid-19 pandemic proved that the best plans are useless if they aren't supported by an implementation plan that is maintained as a "living document" (i.e., made part of ongoing operations) rather than being filed and forgotten. Moreover, even the best implementation plans are ineffective if they haven't been tested to reveal unforeseen implementation problems and if they are not proactive (i.e., implemented before a crisis); once a crisis arrives, it's too late to begin building critical infrastructure and hoping it will work. The well-accepted precautionary principle from risk management (Wikipedia 2020a) reminds us we must prepare now, using the best knowledge we have available, while we work to obtain better and more focused knowledge.

In section 3, I propose solutions to the problems I raise in this section. If you already understand why extreme weather, crop failures, invasive species, a lack of alternatives to open-field agriculture, logistical vulnerabilities, and the associated socioeconomic and political issues are urgent problems, please continue reading with section 3.

2.1 Extreme weather

Climate change is occurring faster than anticipated, and is accelerating. For more than a decade, each new report by the Intergovernmental Panel on Climate Change (IPCC; e.g., IPCC

2020) has been more pessimistic than the previous one. The World Meteorological Organization now predicts a high and increasing risk that within the next 5 years, we will surpass the 1.5°C global temperature rise that many scientists consider the point of no return for irreversible environmental damage (WMO 2020). Climate change is particularly dangerous because it is causing greater changes in the climate extremes (e.g., the maximum daily temperature) than in the average values. Climate change is bringing particular risks related to spring frosts, spring and summer heat waves, inadequate precipitation (drought), and excessive precipitation (flooding).

Spring frosts are dangerous because they occur when plants are most vulnerable to low temperatures, and appear to be becoming an increasingly serious risk due to growing instability of the polar vortex (Unterberger et al. 2018) and the jet stream (Tan et al. 2019; NOAA 2021). Although temperatures warm enough for plant growth to begin are occurring earlier in the year as global warming progresses, late-spring frosts have always been a problem for farmers and are becoming increasingly common. Consider, for example, the 2018 blueberry crop failure in parts of eastern Canada (CBC 2018). Drought is becoming an increasing problem in areas such as California and Arizona that are major sources of fruits and vegetables exported to Canada, and as the climate in western North America continues to dry and temperatures continue to rise, this is leading to water shortages that are driving crop failures or severely reduced yield in these areas. For example, [Canada's canola crop yield decreased by 40% in 2021](#) due to a combination of heat and drought. A recent estimate suggested that [a 40% increase in crop prices since last year resulted from this drought and related factors](#). Simulation studies predict with high confidence that as temperatures warm, yields of corn (maize), rice, wheat, and soybean will decrease by 3 to 11% (Wang et al., 2020).

Spring and summer heat can lead to pollen sterility—the inability of pollen to fertilize female plants and produce seeds, vegetables, or fruits (see section 2.2). Unusual heat can also damage crops even after an edible fruit or vegetable has been produced. In July 2021, CBC reported, with only some exaggeration, that the recent heatwave “[cooked] fruit crops on the branch” (<https://www.cbc.ca/news/canada/british-columbia/heat-fruit-crops-okanagan-fraser-valley-1.6092155>), rendering up to 75% of the crop difficult to use or unusable. Even where the effect of heat isn't so dramatic, it can still greatly reduce crop yields (<https://www.cbc.ca/news/business/canola-wheat-heat-1.6084492>).

Heat also exacerbates the effects of drought. In Canada, a long-term drying trend has been observed, particularly in the west, and this has been documented in the work of Peng Changhui, at the University of Quebec at Montreal, and others (e.g., Peng et al. 2011; Hogg et al. 2017). This phenomenon has contributed significantly to the serious forest fires we've seen in western Canada and in the western U.S. (NRC 2020). The University of Nebraska has provided a compelling visualization of the current status of the western drought and how the drought has progressed over time (<https://droughtmonitor.unl.edu/Maps/CompareTwoWeeks.aspx>).

Note: Drought isn't just a Canadian problem. Many of our fruits and vegetables come from the southern hemisphere, which is also experiencing serious climate impacts. For example, in mid-2021, Brazil's coffee crop suffered heavy losses from drought (<https://www.cbc.ca/news/business/brazil-coffee-drought-1.6096120>). Although coffee isn't a survival food, other crops will also have suffered from the same drought. We'll need to carefully consider how climate change in other regions will affect our food security.

Drought isn't only caused by climate change. Human actions can create or exacerbate drought. For example, Canada's climate plan includes a provision to plant “2 billion trees”

(<https://www.canada.ca/en/campaign/2-billion-trees.html>). This may seem like a great way to remove carbon from the atmosphere, but trees are an unsuitable choice to revegetate any site where water is potentially limited or where forest is not the natural form of vegetation. Work by Cao Shixiong of the Beijing Forestry University and many others (Cao et al. 2010) has demonstrated convincingly that where natural rainfall is insufficient to sustain trees, planting trees exacerbates water shortages. Consumption of soil water lowers the water table, thereby drying the near-surface soil. Shallow-rooted surface vegetation then dies, and the amount of water available to farmers decreases. Given the increasing frequency of enormous forest fires, we must also carefully consider where the trees are planted to avoid creating future conditions that will exacerbate these fires.

Although drought is bad, flooding causes equally serious damage, as occurred in Pakistan in 2022 (https://en.wikipedia.org/wiki/2022_Pakistan_floods). An increase in climate extremes means a greater frequency of excessive precipitation, which can drown crops or beat them to the ground under the force of the rainfall. It can also lead to rotting of field vegetables. Strong winds are often associated with such storms. Severe windstorms are likely to increase in frequency and intensity, as we are seeing already with Atlantic hurricanes. When such storms strike inland areas, as was the case when a windstorm struck the U.S. corn belt in August 2020 (Noor 2020), crops are destroyed, infrastructure is damaged, and lives are lost. There's no reason to believe the Canadian prairies will be safe from such storms. On the contrary, there is evidence that such storms may be increasing in frequency or severity or both (<https://www.ec.gc.ca/meteo-weather/default.asp?lang=En&n=1F934221-1>).

2.2 Crop failures

Crop failures have always been a problem for farmers, and they will worsen as weather becomes more unpredictable and affects wider areas. Canada has been fortunate because, despite occasional localized crop failures, widespread crop failures have not been experienced since the “dust bowl” of the 1930s (Wikipedia 2020b). However, under climate change, crop failure will become increasingly frequent. Moreover, crop failures have historically been scattered, so that if crops failed in one region, they were likely to succeed in another region. However, with changing weather (and particularly changes in the jet stream), the risk of crop failures expanding to more and larger regions (“synchronized crop failures”) is increasing (Kornhuber et al. 2023). The problem recently occurred in Argentina, one of the world's major wheat producers. A heat wave in late 2022 combined with 3 years of drought to severely damage crops, and was expected to cause the loss of half of the 2023 wheat crop (Parshley 2023).

In most crops, the pollen required to fertilize flowers and produce fruits or seeds becomes sterile if the temperature rises above a certain threshold (e.g., Chakrabarti et al. 2009, Mohammed and Tarpley 2011). For key Canadian crops such as wheat (Porter and Gowith 1999) and soybean (Djanaguiraman et al. 2018), the risk of decreased pollen fertility (thus, decreased crop yield) increases as temperatures rise above 30°C, though the critical temperature varies among cultivars and growth periods. Cold temperatures, even if they don't create frost, also pose a danger. For example, the risk that wheat pollen will become sterile increases if spring temperatures drop below 18°C (Chakrabarti 2011).

Heat also increases the risk of crop failures due to drought. For example, more than two thirds of Ontario's apple crop failed after 2012's "summer in March", which was followed by a June drought (CBC 2012). In addition, the drought that endangered agriculture in western Canada in May 2021 (Macintosh and Pauls 2021) appears to be spreading to cover more of our

key farming areas (<https://globalnews.ca/news/7918107/drought-threatens-crops-farms-canada-weather/>). Drought is also occurring again in the U.S., and this has been a long-term problem; Lake Mead's reservoir (which supplies water to 25 million people) has reached the lowest water level ever recorded (<https://www.cnn.com/2021/06/08/weather/hover-dam-lake-mead-water-level-drought/index.html>). Unfortunately, it's not the only large body of water that is shrinking rapidly (<https://gizmodo.com/7-shocking-satellite-images-reveal-the-wests-megadrough-1847080510>).

2.3 Invasive insects and other species

With climate change, Canada is becoming more hospitable to insects for which it was formerly too cold. Insects that affect crops are unfamiliar to most non-farmers. One example is the pea leaf weevil (*Sitona lineatus*), which damages leaves and roots of leguminous plants such as peas and beans. This insect's range in Canada is expanding (<https://www.alberta.ca/pea-leaf-weevil-overview.aspx>). The Japanese beetle (*Popillia japonica*) also causes significant crop damage, and is expected to move northward as Canada's climate warms (Kistner-Thomas 2019).

Even as new insects arrive, others may be disappearing. Preliminary evidence indicates that populations of many ecologically and economically valuable species are declining. Rates of decline are so high that some researchers speak of an "insect apocalypse" (Milius 2020). Insects play an essential role in many ecosystems, and their decline will have both predictable and unpredictable ecological consequences. Many crops depend on insect pollination, and the loss of pollinators (such as bees, now under severe threat from colony collapse disorder) will devastate yields (USDA ARS 2020).

2.4 Lack of alternatives to open-field agriculture

In most of Canada the growing season spans only about 5 months, with production of edible products concentrated towards the end of that period. The overwhelming majority of Canadian agriculture is conducted in open fields, which, combined with the short growing period, makes the crops intensely vulnerable to climate extremes, such as the problems I discussed in section 2.1. An obvious solution would be greenhouses and other forms of sheltered cultivation, but creating enough of this infrastructure to feed a significant fraction of Canada's population of nearly 40 million will require a large investment and considerable time.

2.5 Critical logistical vulnerabilities

We lack a comprehensive understanding of the weak links in the political, social, and logistical chains that produce food for Canadians. Some of these links may represent single points of failure for which protections and alternatives must be found. For example, stored refrigerated food can last a long time, but extreme weather will increase the frequency of power outages that can endanger this food. Food storage and transshipment facilities that don't already have backup power sources will be particularly vulnerable. The Covid-19 pandemic revealed that truckers, train network workers, and the crews of cargo ships are essential links in the logistics chain. The American shortage of infant formula in May 2022 revealed the danger of single points of failure.

We will need researchers with advanced expertise in logistics to identify these weak links so we can begin prioritizing problems and developing solutions, finding ways to make the food system more resilient against failure, and developing strategies for coping until these solutions are available.

2.6 Socioeconomic and political issues

The Covid-19 pandemic highlighted that the poorest and most vulnerable people are particularly threatened when food costs increase. During the pandemic, these increases primarily resulted from logistical problems (e.g., difficulties getting enough workers to harvest the crops and transport them to markets). Under climate change, costs will increase for additional reasons, such as a decreased supply (i.e., crop failure) and the increasing cost of trying to protect crops against the threats described earlier in this white paper. Crucial agricultural inputs such as fertilizer increased dramatically in price, particularly after the war in Ukraine cut off access to a major global fertilizer source in 2022. Our experience with providing financial support to individuals and institutions during the pandemic should be used to plan a comparable safety mechanism to ensure that all farmers can afford to purchase such inputs and that all Canadians can afford to buy enough food.

The traditional solution to local crop failures has been to buy crops grown elsewhere. Canada is fortunate in having enough wealth to make this possible—under current conditions. But crop failures may also occur outside of Canada in regions essential to our food security. For instance, California is a primary source of fruits and vegetables for Canada. The severe drought the state experienced from 2012 to 2016 caused an estimated economic loss of \$US45 billion and the loss of more than 21,000 agricultural jobs (National Geographic, no date) and the drought appears to have returned in 2021 (<https://ucsdguardian.org/2021/05/02/drought-returning-to-california/>). Similar problems have begun to affect crop production in the southern hemisphere, another important source of fruits and vegetables for Canada. We may soon be unable to count on these crops if ours fail.

These water shortages are also a large and growing issue in key American agricultural regions such as the Midwest. The Ogallala aquifer (Wikipedia 2020c)—the primary source for irrigation of the U.S. Great Plains corn belt and breadbasket—is heavily overexploited. Recent estimates suggest that current rates of consumption will deplete this reservoir within 20 years. Since abandoning this land is not feasible, the U.S. will likely try to irrigate the land with water from the Great Lakes. (The geography is unfavorable, since watersheds drain downhill into these lakes, and pumping water uphill against gravity would be a very expensive engineering project. Nonetheless, given how aggressively the U.S. subsidizes its agricultural sector, it seems unlikely they wouldn't subsidize such a project.) There's no short-term risk of draining a body of water as large as the Great Lakes, but large-scale withdrawals will severely damage the lake ecosystems, and will have significant negative effects on the regional climate.

The U.S. government has badly mismanaged the Colorado River and the associated conflicts over allocation of its water (Gelt 1997); there is no reason to think it would manage the Great Lakes any better. Canada negotiated a ban on such bulk water exports more than 2 decades ago (Johansen 2002), but given the magnitude of the potential problem and the traditional American reluctance to be constrained by considerations such as Canadian sovereignty, we need to revisit this issue.

Water supplies are also at risk elsewhere in the world. Aquifers are becoming depleted outside of North America too. For example, in 2018, Chennai, India's 6th largest city, depleted its aquifers (Noor 2021), and climate researchers predict an increasing risk that the monsoon rains in Asia will periodically fail in countries such as India (Schewe and Levermann 2012), although there is considerable uncertainty (Lenton et al. 2008). There is concern that similar problems may affect the Asian summer monsoon (Takaya et al. 2021). These trends put millions of people at risk of starvation. If crops fail in India, how can we transport enough food to feed

more than 1 billion people? In July 2023, India restricted exports of white rice out of fear that rice crops would decrease as a result of drought caused by the coming El Niño event, and Asian countries have begun stockpiling rice in anticipation of this problem (GPF 2023). Africa faces similar problems.

It's important to remember that although the temptation is to focus on problems related to drought, all that water has to go somewhere else. As we saw during the August 2022 floods in Pakistan, drought in one place often means flooding elsewhere. Other factors related to global warming can exacerbate the flooding problem. For example, global warming is producing warmer air that can hold more moisture, leading to heavier rainfall, and that is accelerating melting of glaciers, leading to greater peak flows in rivers (Mallapaty 2022).

We cannot assume that we will be able to outbid other wealthy nations, such as the U.S., or groups of nations, such as the European Community, if we find ourselves competing for a globally constrained food supply. Indeed, many of our key suppliers may be forced to stop exports so that they can feed their own citizens. Moreover, serious humanitarian and ethical considerations will arise if we find ourselves competing with developing nations, such as most of southern and eastern Asia. Many developing nations already have low food security, and will compete aggressively for future access to food. For example, China is working to bolster its own food security through its enormous “Belt and Road” initiative (CFR 2020), which includes a component intended to secure grain supplies and other goods from Europe (OECD 2018).

Climate change and the resulting famines will increase ecological migration, in which natural catastrophes such as drought and flooding drive people to flee their homes and their home countries. Canadians are justifiably proud of the welcome our country offers to immigrants. Unfortunately, the number of people displaced by ecological migration will become an increasingly serious problem as tropical and subtropical climates warm and more and more people can no longer survive on their original land (<https://www.cbc.ca/news/science/what-on-earth-trees-climate-refugees-1.6034396>). Canada’s recent experience with Syrian refugees shows how difficult (slow and expensive) it was to resettle only 50,000 people. The wars in Afghanistan and Ukraine created similar refugee crises. Mass migrations are likely to become a global crisis that affects tens of millions of people within a few decades, and large investments will be needed to build the infrastructure necessary for Canada to welcome, integrate, and benefit from this influx. Among other things, we are currently facing a severe housing shortage, and without immediate measures to increase the housing supply, it will become increasingly difficult to house immigrants.

Covid-19 has reminded us of the increasing risk of global pandemics, but other health issues, both for migrants and for people already in Canada, will become ongoing concerns. Among other things, undernourished and malnourished people become more vulnerable to disease. The editorial board of the venerable and renowned British medical journal *The Lancet* has begun discussing the health impacts of climate change (Lancet Editors 2020), and we should use this discussion as a starting point for our own discussion.

3. Potential solutions

Given the problems described in section 2, Canada must immediately begin taking measures to safeguard our food production against the impacts of climate change, with an eye toward achieving self-sufficiency. Many lessons learned in the Covid-19 pandemic will be applicable here; logistical systems developed for nationwide vaccine distribution, for instance, can suggest systems for nationwide food distribution. Perhaps most importantly, we must move

beyond frameworks that are functionally inaction plans to develop action plans. Learning from history means examining and learning from previous pandemics and other disasters so we can avoid repeating previous mistakes. As Kelman et al. (2023) demonstrate, "disasters avoided" are better than disasters that we retroactively respond to.

I will be expensive to protect our food security against climate change. It will be far more expensive, in dollars and lives, to do nothing and wait for a crisis. Thus, we must find economically efficient solutions that Canada can adopt now, and that can be phased in over a period of years to spread out the cost. Now is the time to act, while our agricultural situation is stable. Wherever possible, such solutions should be designed to mostly or completely pay for themselves. Gradual implementation will also be far less expensive than a crisis response. In this section, I propose potential solutions to the problems identified in section 2. This list is not comprehensive; more work needs to be done to identify the most effective and cost-efficient solutions.

Note: Smith (2022) provides a comprehensive discussion of strategies to mitigate and adapt to climate change, including a section on agricultural strategies.

3.1 Mitigate the effects of extreme weather

We can't control the weather, but we can prepare for its consequences. For example, Agriculture Canada scientists should identify cultivars of our key crops that have high resistance to spring frost, summer heat, windstorms, and both drought and flooding. Farmers will only adopt these cultivars if they grow efficiently and produce sufficiently high yield under the current climate. If such cultivars don't already exist, they should be developed through strategic breeding programs, perhaps in cooperation with experts around the world. For example, we should begin to identify and encourage the production of crops that are highly tolerant to heat. Canadian researchers have been working to [develop heat-tolerant canola cultivars](#), and a similar effort should be focused on other essential crops. Several crops grow well or even thrive at temperatures in the 30s and 40s (°C): eggplant (especially Mediterranean varieties), hot peppers, squashes and zucchini, okra, sweet potatoes, and sunflower. (Sunflower not only produces valuable seeds and oil, but offers the additional advantage of attracting many agricultural pests away from the main crop.) Cherry tomatoes may also thrive, and may therefore represent a suitable replacement for larger tomatoes.

Mitigating the problem of drought could begin with simple changes to traditional farm systems. For example, storing water in uncovered large-area ponds greatly increases evaporative water loss, particularly in warm and windy weather. Finding ways to cover existing ponds or converting such ponds into cisterns that protect the water against evaporation will be essential. There are also growing numbers of high-tech ways to harvest water from the atmosphere (e.g., Daley 2021; Haechler et al. 2021) that should be investigated, perhaps through field trials with small-scale farmers before expanding the trials to cover larger cultivated areas.

Other climatic extremes may have solutions based on improving or replacing traditional agricultural techniques. For example, in areas vulnerable to flooding, improved drainage may be an inexpensive solution. In areas prone to frost, it may be possible to use techniques such as continuous irrigation, particularly at night (because water releases substantial amounts of heat when it freezes), and instead use external sources of heat (such as "heat lamps") powered by solar batteries that store energy during the day.

3.2 Compensate for crop failures

We can't prevent widespread crop failures if we rely entirely on open-field agriculture, but we can develop strategies to cope if a crop failure occurs. One strategy would be to extend existing guidance on disaster responses, such as hurricane preparedness (State of Florida 2020), by encouraging individuals and families to do some of the preliminary work to store food. Guides to doing this already exist (e.g., Brigham Young University 2019) and can be modified and updated to account for cultural preferences. In the context of food security, we should provide clear guidelines to households on how to gradually accumulate and safely store 6 months to 1 year of a nutritionally complete diet, so that if a food shortage makes rationing necessary, many people will already be prepared. This approach will not be feasible for many Canadians (because of the cost or a lack of adequate storage space), but if even a fraction of Canadian households can do this, it will be easier to allocate the remaining food to those who need it most. Moreover, existing food bank programs could be given incentives to increase their storage of nonperishable food to ensure that our poorest families will have continuing access to food.

In a crisis, this approach would give us time to implement a “Manhattan project” (https://en.wikipedia.org/wiki/Manhattan_Project)—an intense, short-term project designed to restore food production. For example, if we begin studying small-scale greenhouses and other alternatives now (see section 3.4 for details), we will gain the experience required to rapidly build large numbers of greenhouses and indoor farms. To do this, we must create and test such projects now so we can identify and eliminate impediments to wide-scale implementation.

We may also need to provide incentives to rebalance crop production to reduce the proportion of our crops allocated to livestock fodder and increase the human food supply. In a famine, food should be allocated preferentially to humans, not livestock. For example, in some areas, it may be necessary to switch from crops like corn that primarily support livestock or ethanol production to more nutritionally complete foods like soybean that can support humans. (Existing marketing boards are both a problem, because of the constraints they impose, and an opportunity, because they have long experience with the practicalities of food storage and distribution.)

Note: Crop insurance is designed to help farmers get back on their feet after a bad year or crop failure. Although this solves the *economic* problem of crop failure, it does not solve the social problem of providing food to replace lost or damaged crops. Thus, it's essential that we look beyond crop insurance to provide *food insurance*—that is, strategic stockpiles that can be used to replace failed crops.

Although humans can survive on a purely vegetarian diet, eliminating meat consumption should not be necessary. (This compromise would encourage people who currently eat meat to support plans to shift towards consumption of more vegetable protein.) A supply of animal protein for human consumption can be provided by promoting husbandry of goats and chickens rather than cattle, since both animals can eat all kinds of scraps, rather than purpose-grown fodder, and can turn that waste matter into high-quality protein (milk and meat for goats, eggs and meat for chickens). Given the high nutritional quality of fish, combining aquaculture with greenhouse production of crops (see section 3.4) may be another efficient solution. For example, Singapore is building a large indoor aquaculture facility capable of supplying 3 million kilograms of fish annually (Pescovitz 2021). A similar project has begun in Montreal, though on a smaller scale (<https://district-central.ca/en/actualites/articles-en/opercule-a-fish-farm-in-the-heart-of-the-city/>); with government assistance, this project could be expanded. The effluent from such facilities, which is currently seen as a waste product that requires expensive treatment,

can be routed through greenhouses. The plants and soils will filter out fish urine and feces, which are powerful fertilizer, and the purified water can then be returned to the aquaculture facility (Joyce et al. 2019). This approach can be implemented both in conventional soil-based agriculture and in hydroponics systems.

3.3 Monitor invasive species and key native species

Researchers must continue to identify and monitor invasive insects, plant and animal diseases that threaten crops, and agricultural weeds that have been migrating slowly northward as temperatures have risen. This will help us understand what problems to anticipate instead of being surprised by them when they occur. Efforts such as that by Agriculture and Agri-foods Canada (AAFC 2020) will be increasingly important, but only if they are supported by action plans. We must also develop plans to respond to the appearance of these threats in Canada before they establish a foothold.

Note: Native species that don't usually make the news will also be a problem. For example, while I was revising this white paper in July 2021, farmers in Winnipeg had begun reporting a plague of grasshoppers—which is what Manitoba's Agriculture Department predicted would happen if the province suffered from unusually hot and dry conditions

(<https://www.gov.mb.ca/agriculture/crops/insects/grasshopper-forecast.html>).

Warm temperatures increase the over-winter survival of insects, thereby leading to larger populations in the spring. When this is combined with stressful temperatures (too hot or too cold for plants) and excessive or insufficient soil water, plants are under severe stress that makes them more vulnerable to insects. As the frequency and severity of extreme weather increases, so will the risk to crops.

While some dangerous species are multiplying and spreading, others that are critical to our ecosystem are endangered and may even be disappearing. As I noted earlier, we may already be experiencing an “insect apocalypse”. We must investigate the scale of this danger and determine which species are most vulnerable. We must protect essential species, such as pollinators, by setting up “wildlife refuges” where they can rebuild their populations and by creating industrial or laboratory colonies that we can use as breeding populations to support their reintroduction into the wild. Such facilities already exist, such as the Forest Pest Management Institute's Insect Production and Quarantine Laboratories (<https://www.nrcan.gc.ca/science-and-data/research-centres-and-labs/forestry-research-centres/great-lakes-forestry-centre/insect-production-and-quarantine-laboratories/13467>) and the U.S. Department of Agriculture Insect Rearing Facility (<https://www.ars.usda.gov/plains-area/brookings-sd/ncarl/ncarl-links/insect-rearing-facility/>).

This will be particularly important for key domesticated species such as honeybees and their wild relatives (e.g., solitary bees). Projects should be developed to support the transport of bees and other critical pollinators to agricultural areas around the country. Alternatively, breeding facilities should be established in each province to reduce the need for cross-border transport and to avoid putting all our eggs in one basket. Expertise gained from insect breeders who provide biological control services to fight insect pests of crops can be applied to the production of essential agricultural insects.

3.4 Develop and implement alternatives to open-field agriculture

Greenhouses are an obvious solution to the vulnerability of crops grown in open fields, and they can produce harvests year-round. However, they would be challenging to implement on a large scale in Canada because of our climate. Greenhouses require large energy inputs to maintain optimal temperatures during cold winters and prevent heat damage during the increasing number of hot summers. They are also vulnerable to severe weather, such as hailstorms and strong winds, and such extreme events will become more frequent in coming years. Despite these problems, greenhouses are increasingly popular. For example, Québec has begun an initiative to promote greenhouse production (Gagné 2021) with the goal of increasing domestic food security; to do so, they are offering financial incentives such as greatly reduced electricity costs. The change to sheltered (indoor) cultivation could happen surprisingly quickly and at a surprisingly low cost. In 2020, Québec invested \$100 million to double its greenhouse capacity, plus rebates on an unspecified percentage of energy costs. By 2023, the province's growers supplied 50% of its vegetable demand, up from 30% in 2020 (Wheeler 2023). This program should be examined at a national level after learning from Québec's experience.

Innovative alternatives exist, such as “indoor (factory) farms” that use artificial lighting (Kozai 2018), and that don't require fragile glass or plastic roofs. Recently, an Ohio company created a large, fully automated indoor farm that covers 3.5 acres (Drotleff 2018). There are higher-technology options, such as the products of the Canadian company CubicFarms (<https://cubicfarms.com/>). See section 3.6 for some related suggestions. Large-scale greenhouse cultivation has been successfully implemented in Spain's Almería project (Wikipedia 2020d), although there are problems that must still be solved. Nonetheless, we can learn from their experience. Entrepreneurs have also begun testing the economics of using greenhouses to provide fresh produce to restaurants throughout the year. Their expertise will support wider implementation of such an approach, possibly with government funding.

In some areas it will be viable to grow crops underground in abandoned mines, where they are protected from severe weather and maintain a nearly constant temperature throughout the year. In Canada, Inco tested this approach in Sudbury, and found that the economics weren't favorable (Mining Matters, no date). But the prospect of severe food shortages would change the evaluation. The Hudson Bay Smelting and Mining Company had better results with higher-value crops (e.g., fresh herbs such as basil) in Manitoba (Ramirez 1995).

Hydroponics is another option, particularly when implemented in structures such as shipping containers that are highly resistant to hazards such as hail. This may be particularly attractive in remote communities (CBC 2020), alone or in combination with greenhouse designs that are well adapted to our northern climate (Veillette 2019).

3.5 Solve critical logistical vulnerabilities

Experts in disaster preparedness and community resilience should be hired as consultants to identify key links in the food supply chain, examine them for weaknesses, and develop ways to strengthen the links and mitigate any weaknesses (Pittis, 2020). The expertise of logistics professionals will also be important. Now would be a good time to review the status of Agriculture Canada's Crop Logistics Working Group (AAFC 2021) and provide the necessary resources to expand its capacity. Some solutions will be relatively simple, such as encouraging food storage and transshipment facilities that lack backup power supplies to purchase backups, possibly supported by government subsidy programs.

3.6 Consider socioeconomic and political issues

One intriguing solution to a potential future food shortage results from the fact that many recent immigrants and refugees are displaced farmers. One way to help these people become economically self-sufficient more quickly would be to provide loans, grants, or other forms of support to construct large greenhouses or indoor farms and train these displaced farmers to transfer their skills from field agriculture to face the different challenges of indoor cultivation. Other Canadians should also be encouraged to try this approach.

This approach would provide steady and lucrative employment that will repay the government's investment in bringing these people to Canada and establishing production facilities they can operate. Moreover, because most of our fresh fruits and vegetables come from outside Canada during the winter, greenhouse farmers won't initially be competing with Canadian farmers; instead, they will be competing with foreign, primarily American and South American, producers. This will reduce tensions between the immigrants and the pre-immigration population, will reduce our dependence on external sources (e.g., California, Brazil), and will increase food security by providing year-round nutrition.

The same approach could easily be extended to Indigenous peoples and others who live in remote areas, where obtaining fresh vegetables is both difficult and very expensive. Individual households can also set up their own indoor or underground farms, potentially at a cost of less than \$10,000 per household, as has been demonstrated in Quebec (Veillette 2019). Though that's not a small investment, it would be amortized over a decade or more, making it more economically practical. In addition, economies of scale would greatly reduce this cost as demand increases. Since (for historical reasons) Indigenous communities are far more vulnerable than other communities, we should prioritize efforts to help them achieve food security (CBC 2020).

A final consideration, which we learned during late 2021, is that food prices can be expected to increase greatly as crop failures begin to occur more often (<https://www.cbc.ca/news/business/canola-wheat-heat-1.6084492>). Just as the government created emergency economic support programs for unemployed Canadian during the covid-19 pandemic, it will be necessary to plan to support the most vulnerable members of society, who already have difficulty affording healthful and nutritious food.

4. A call to action

The biggest failure of Canada's Covid-19 response was that even though response plans had been drafted after the MERS and SARS outbreaks, they were shelved and forgotten. A senior Canadian risk management specialist (<https://www.bcpriskmanagement.ca/>) tells me there have been many documents that agree on the need for action to increase food security or that provide frameworks for such action, but there has been no implementation plan that addresses the issues I've raised. Such an implementation plan must clearly identify the key deliverables, the names of the people who are responsible for providing those deliverables, and the timetable for delivery.

An underappreciated problem is the difficulty of communicating complex science to the governments that will be required to based their policy decisions on that evidence. Most scientists lack the training to succeed in this communication, and the problem is exacerbated by the fact that politicians often lack sufficient science education to understand what the scientists are trying to say (Sanderson 2023). We will need skilled communicators capable of communicating both the urgency of the need to act and the evidence that justifies the need for action.

All of the recommendations in this white paper must become ongoing responsibilities that are part of the operations of the relevant federal and provincial ministries; any action plans that result from this white paper must become living documents that are part of standard operating procedures and that are updated regularly, with new deliverables, delivery dates, and responsibilities. If not, they will become archival documents that are quickly forgotten. The plans must be reviewed with each change of government, and ideally more frequently, to ensure that they remain valid, to identify problems that must be solved, and to identify new solutions that have become available.

I'm making these recommendations now because it takes years to move from well-meaning discussion documents to implementation plans. It took England nearly 10 years to end food rationing after World War II. Infrastructure takes a particularly long time to plan and implement, and requires long-term funding. Given these delays and costs, we need to start now—as the Covid-19 pandemic showed us, we can't afford to wait until a crisis occurs. Because we can't know when an agricultural crisis will arrive, proposed solutions should ideally be rational, efficient, and cost-effective under *current* conditions. They should be tested on a small scale to confirm that they work and to identify problems that should be solved before large-scale implementation. Then they should be implemented widely so they are in place when the crisis arrives.

On behalf of Canadians, not to mention our fellow humans elsewhere, I call on you to work with experts on each of the issues described in this white paper to ensure that we are able to respond rapidly and effectively to the climate crisis.

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