



1 **Cross-border exposure of Canada's fruit and vegetable supply to future**
2 **weather extremes**

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13 **Key Points:**

- 14 • We developed provincial-scale fruit and vegetable supply-chain data for Canada covering
15 2010–2022.
- 16 • Regions that supplied Canada's fruits and vegetables in 2018–2022 are projected to
17 experience changes in agroclimatic indicators under future climate change.
- 18 • Canada's fruit and vegetable supply chains are exposed to worsening agroclimatic
19 conditions in the future.
- 20 • Exposure varies by Canadian province, fruit or vegetable commodity, sourcing region,
21 and agroclimatic indicator.

22



23 **Abstract**

24 Fruit and vegetable supply is essential for a healthy diet, yet the exposure of supply chains to
25 climate-related conditions is often overlooked, particularly when sourcing crosses national borders.
26 We develop provincial-scale food flows for 18 fruits and 16 vegetables using average 2018–2022
27 production and trade data, including estimated interprovincial flows and derived products. We then
28 link these recent sourcing patterns to changes in maximum five-day rainfall, consecutive dry days,
29 days below 0°C, and days above 35°C from +1°C to +3°C global mean warming relative to 1850–
30 1899. Across Canada’s supply, 43% of fruit and 19% of vegetables are sourced from regions
31 projected to experience at least 15 additional days above 35°C, 19% and 8% from regions with at
32 least five additional consecutive dry days, 31% and 9% from regions with at least a 5% decrease in
33 maximum five-day rainfall, and 7% and 2% from regions with at least 10 fewer days below 0°C,
34 respectively. Exposure is concentrated in specific supply chains, including lettuce sourced from
35 California and Arizona and avocados from Mexico, and varies across provinces because of
36 differences in sourcing portfolios. This exposure assessment holds recent sourcing patterns constant
37 and does not estimate crop-yield losses, future trade adjustments, prices, or supply disruptions. It
38 provides a basis for identifying the most exposed commodity, province, and source regions that may
39 warrant more detailed impact and adaptation assessment.



40 **Introduction**

41 Fruits and vegetables are an integral part of a healthy diet. The World Health
 42 Organization recommends that people eat 400 g of fruits and vegetables per day, excluding
 43 starchy vegetables such as cassava and potatoes (WHO, 2021). Canada's food guide also
 44 recommends that half of daily food intake consist of fruits and vegetables (Health Canada, 2019).
 45 Despite the known benefits, only a small percentage of Canadians buy sufficient quantities of
 46 fruits and vegetables to meet the recommendations in Canada's Food Guide (Charlebois et al.,
 47 2023). At the same time, national availability of fruits and vegetables for consumption has
 48 declined over the last ten years (Statistics Canada et al., 2020). According to a recent survey, the
 49 cost of fruits and vegetables, together with limited knowledge and preparation skills, are leading
 50 drivers of low fruit and vegetable consumption in the country (Charlebois et al., 2023). To create
 51 an enabling environment for healthy diets, the availability of and affordable access to fruits and
 52 vegetables, though insufficient on their own, are important.

53 The global supply of food, including fruit and vegetable supply to Canada, is produced
 54 through an interconnected and complex system (Nature Food, 2022). Supply-chain innovations
 55 and technologies, such as just-in-time logistics and standardization, have increased the efficiency
 56 and connectivity of global supply chains (Berfin Karakoc & Konar, 2021; D'Odorico et al.,
 57 2014; Kummu et al., 2020). International trade contributes to nutritional security in many
 58 countries, including Canada (Wood et al., 2018). At the same time, greater connectivity can
 59 transmit shocks across sourcing regions and importing markets (Bernard de Raymond et al.,
 60 2021; Ercsey-Ravasz et al., 2012; Gaupp, 2020b; Tu et al., 2019). Shocks in major food-
 61 producing regions can affect distant importers (Ercsey-Ravasz et al., 2012; Heslin et al., 2020;
 62 Puma et al., 2015). Such interconnected effects have also been observed during disruptions to
 63 Ukrainian grain exports (Clapp, 2023; Laber et al., 2023), increases in global fertilizer prices
 64 (WTO & FAO, 2022), and the 2007–2008 food crisis (Headey, 2011; Martin & Anderson, 2012).
 65 In Canada, recent disruptions to lettuce and avocado supply illustrate why the geography of
 66 sourcing matters (Bloomberg, 2022; CBC, 2022). These examples motivate our assessment of
 67 exposure across fruit and vegetable supplying regions of Canada.

68 Climate change and weather shocks may intensify pressures on interconnected food
 69 systems. However, climate assessments and adaptation policies are often framed nationally and
 70 may therefore understate conditions occurring in the regions from which imported food is



71 sourced (Benzie & Persson, 2019; Challinor et al., 2017). In this study, exposure refers to
 72 weather conditions or changes in conditions in the regions contributing to Canada’s fruit or
 73 vegetable supply. Exposure alone does not imply an impact, vulnerability, or risk: outcomes also
 74 depend on crop sensitivity, the timing and duration of weather conditions, production practices,
 75 adaptation, market responses, and substitution. We therefore present a preliminary assessment of
 76 the exposure of Canadian food supplying regions to changes in agroclimatic conditions related to
 77 climate change rather than a prediction of production losses or holistic climate risk assessment.

78 Canada’s food system provides an illustrative setting for assessing cross-border exposure.
 79 Although Canada is a net exporter of food, 80% of its fruit supply and 60% of its vegetable
 80 supply depend on international trade (Kissinger, 2012). Here, we estimate exposure for fruit and
 81 vegetable supply to Canadian provinces using recent food flows and four projected agroclimatic
 82 indicators. We integrate novel food-flow estimates that map the supply of 18 fruits and 16
 83 vegetables from every country, US States, and within country to Canadian provinces (available
 84 through an interactive tool at <https://canadafoodflows.ca/>), with ensemble climate-model
 85 estimates for maximum five-day rainfall, consecutive dry days, days below 0°C, and days above
 86 35°C. The food-flow estimates account for international trade, estimated interprovincial
 87 redistribution, and derived products. We compare conditions at +3°C with those at +1°C global
 88 mean warming relative to 1850-1899, representing approximately 2°C of additional warming.
 89 Our analysis makes two contributions: we develop provincial-scale supply estimates for 18 fruits
 90 and 16 vegetables and use those estimates to assess the exposure of provincial supply to future
 91 agroclimatic indicators based on latest downscaled and bias corrected multi-model climate
 92 projections. Recent 2018-2022 sourcing patterns are held constant, so the analysis is diagnostic
 93 rather than a forecast of future trade or production. We report results for all included
 94 commodities; where prior evidence on biophysical sensitivity is unavailable, the exposure results
 95 should be interpreted cautiously (Table S1).

96 **2 Materials and Methods**

97 We first estimate recent provincial-scale food flows, accounting for derived products and
 98 estimated interprovincial redistribution. We then link these flows to projected agroclimatic
 99 indicators in all supplying regions. The two components together provide a preliminary measure
 100 of exposure under fixed recent sourcing patterns.



2.1 Food flows data

A substantial body of research estimates national food flows to assess the sustainability and resilience of food supply chains (Davis et al., 2021; Kastner et al., 2021), but few studies resolve flows at subnational scales (Schreiber et al., 2021). Dall’erba et al. (2024), Karakoc et al. (2022), and Lin et al. (2019) estimated food flows between U.S. counties using detailed modelling approaches that require data often unavailable elsewhere. Dalin et al. (2014) and Harris et al. (2020) used optimization approaches to estimate subnational flows in China and India, while Pandit et al. (2023) estimated detailed trade between U.S. counties and Chinese provinces. Commodity-specific systems have also been developed for U.S. corn (Smith et al., 2017), Brazilian beef (zu Ermgassen et al., 2020), soy (Godar et al., 2015), Ivorian cocoa (Renier et al., 2023), and Indonesian palm oil (Benedict & Heilmayr, 2024). These studies differ in commodity scope, data requirements, and whether subnational detail is resolved at production origins or consumption destinations. We use a transparent mass-balance allocation approach designed for a data-constrained setting and apply it across multiple fruits and vegetables at the Canadian provincial consumption end. The principal contribution is the resulting provincial dataset and its integration with climate-exposure indicators, rather than a wholly new class of flow model. Beyond a few regional reports (Metro Vancouver & Davies Transportation Consulting Inc., 2020; RECYC-QUÉBEC, 2022), comprehensive commodity-specific provincial food flows for Canada have been largely absent.

To develop provincial-scale food flows for Canada, we used a mass-balance approach integrating production, imports, and exports of fruit and vegetable commodities while accounting for estimated interprovincial redistribution and derived commodities. The complete dataset covers 2010–2022. For the exposure analysis, we used the most recent five-year average available at the time of analysis, 2018–2022, to characterize recent sourcing patterns and reduce the influence of anomalies in any single year. This average is used as a fixed baseline and is not intended to represent future sourcing. Supplementary Text S1 provides a detailed explanation.

We obtained production and trade data for 18 fruits and 16 vegetables, representing 88% and 87% of total fruit and vegetable consumption in Canada, respectively. Provincial production data were sourced from the Fruit and Vegetable Survey, the Annual Greenhouse, Sod and Nursery Survey, and the Biannual Potato Area and Yield Survey. Bilateral trade data for the same commodities and period were obtained from the Canadian International Merchandise Trade Web Application provided by Statistics Canada.



132 We harmonized production and trade data to estimate provincial supply for consumption.
133 The datasets use different classification systems and temporal resolutions. Provincial customs-
134 based trade data use the Harmonized System classification (UNSTATS, n.d.) and are available
135 monthly, while provincial production data use the North American Product Classification System
136 (Statistics Canada, n.d.) and are available annually or biannually. After preprocessing, we
137 matched production and trade codes to FAO Item Codes using the FAO correspondence key and
138 commodity descriptions. Supplementary Text S1 provides the matching key and further details.

139 Provincial bilateral trade data could not be used directly to estimate final provincial
140 supply. First, customs-based trade data identify the province of clearance, where a commodity
141 enters and is cleared at the Canadian border, rather than necessarily its final provincial
142 destination (Government of Canada, 2025). Second, the primary datasets do not observe
143 interprovincial redistribution from provinces of clearance or production to provinces of
144 consumption.

145 We addressed these limitations by estimating interprovincial redistribution through a
146 mass-balance allocation. We assumed that annual per-capita consumption of each commodity
147 was equal across provinces and set it to national per-capita consumption, using provincial
148 population estimates from Statistics Canada. This is an allocation assumption rather than an
149 observed dietary pattern. We identified provinces whose production and cleared imports
150 exceeded estimated provincial requirements as supply hubs and provinces with deficits as hub-
151 dependent provinces. Excess supply was distributed to deficit provinces using inverse road
152 distance between key cities as weights. The resulting flows are modelled allocations and should
153 not be interpreted as observed commercial shipment routes.

154 Finally, we traced redistributed supply from hubs back to the regions contributing to each
155 hub's supply shares and adjusted the original producer-to-hub flows to avoid double counting.

156 Food-flow model evaluation and sensitivity analysis. We evaluated the equal per-capita
157 consumption assumption using NielsenIQ MarketTrack aggregated annual sales quantities for
158 four fresh fruits and three fresh vegetables across Canadian provinces from 2019 to 2022.
159 Although these data do not capture all produce purchases, they provide an alternative estimate of
160 provincial differences for the seven commodities. We recalculated flows using the sales-
161 informed provincial patterns and compared them with estimates based on uniform per-capita



162 consumption. The resulting supply shares and quantities were broadly similar for most
 163 commodity–province combinations, with exceptions shown in Figures S1–S8. This sensitivity
 164 analysis evaluates the influence of one modelling assumption but is not an independent
 165 validation of physical shipments. The model is also internally consistent with the national
 166 production, import, and export quantities used as inputs.

167 **2.2 Future agroclimatic indicators**

168 To estimate agroclimatic exposure over global cropland during growing seasons, we used
 169 bias-corrected and downscaled climate-model simulations at 0.25° spatial resolution from the
 170 Coupled Model Intercomparison Project Phase 6 (CMIP6). The Climate Impact Lab dataset uses
 171 bias-correction and downscaling methods designed to preserve trends without amplifying or
 172 damping extremes (Gergel et al., 2024).

173 We used nine CMIP6 simulations for the SSP2-4.5 scenario, accessed and analysed
 174 through Microsoft’s Planetary Computer. From the 25 available models, we retained nine whose
 175 transient climate response fell within the recommended likely range of 1.4–2.2°C (Hausfather et
 176 al., 2022), excluding models outside that range. Transient climate response is the amount of
 177 global warming reached when atmospheric CO₂ concentration doubles after increasing by 1%
 178 per year (Hausfather et al., 2022).

179 We selected four agroclimatic indicators spanning precipitation and temperature
 180 conditions: maximum five-day rainfall; the maximum number of consecutive dry days using a
 181 threshold of less than 1 mm of rainfall per day; the number of days with minimum temperature
 182 below 0°C; and the number of days with maximum temperature above 35°C. These indicators
 183 provide standardized exposure measures and are not treated as universal crop-damage thresholds.
 184 We masked the data to cropland (Ramankutty et al., 2008) and to simplified growing seasons: all
 185 months in the tropics, April–September north of 30°, and October–March south of 30°. The mask
 186 deliberately uses general cropland and broad seasonal windows because future cultivated areas
 187 and seasons are unknown. It therefore does not identify crop-specific production locations or
 188 phenological stages. For each model, we calculated 30-year median annual values around the
 189 first year that the model reached +1°C and +3°C global mean warming relative to 1850–1899,
 190 using threshold years from Hausfather et al. (2022). We then calculated percentage changes for



191 the precipitation indicators and absolute changes for the temperature indicators from +1°C to
 192 +3°C and summarized the models using the ensemble median.

193 **2.3 Consumption-based, within-Canada, and cross-border exposure**

194 For each administrative unit, domestic production exposure is calculated as the average
 195 agroclimatic indicator over its cropland. A commodity's contribution from an administrative unit
 196 is assigned zero weight when that unit supplies none of the commodity; this does not imply that
 197 the commodity's overall supply has zero exposure. For each province and commodity,
 198 consumption-based exposure is calculated as the supply-share-weighted average across all
 199 within-province, interprovincial, and international sourcing regions. Interprovincial exposure is
 200 calculated using only sourcing regions elsewhere in Canada, weighted by their shares of the
 201 province's total interprovincial supply of that commodity. Cross-border exposure is calculated in
 202 the same way using only international sourcing regions, weighted by their shares of the
 203 province's total international supply of that commodity.

204 To compare Canadian and international contributions at the national scale, we aggregated
 205 food flows across provinces. Within-Canada exposure is the supply-share-weighted average
 206 across Canadian sourcing regions, while cross-border exposure is the corresponding average
 207 across international sourcing regions. Together, these components form the national
 208 consumption-based exposure estimate for each commodity. All estimates use average 2018–2022
 209 food flows.

210 **3 Results**

211 **3.1 Canada sources most fruits and a large share of vegetables internationally**

212 Using our estimated food flows, we identify from where and how much Canadian
 213 provinces source their fruits and vegetables (Figure 1, see Figure S9 for all 18 fruits and 16
 214 vegetables). We find distinct variations in the proportion of supply sourced from international,
 215 interprovincial and domestic (provincial) regions across provinces and types of produce.

216 For fruits, we find the dependence on international imports across provinces is highest for
 217 bananas (100% supply share), oranges (100%) and watermelons (80% to 100%). This is
 218 followed by apples (11% to 66%) and grapes (37% to 76%) and is lowest for blueberries &



219 cranberries (0 to 28%). We also observe significant interprovincial supply (interprovincial trade)
 220 of apples, grapes, blueberries and cranberries to the prairie provinces (Alberta, Saskatchewan
 221 and Manitoba) and Atlantic provinces (Newfoundland & Labrador, New Brunswick, Nova
 222 Scotia and Prince Edward Island). For apples and grapes, the interprovincial supply share of the
 223 prairie provinces ranges from 52% to 65% and 22% to 63% respectively, and for the Atlantic
 224 provinces from 51% to 69% and 29% to 36%, respectively. Similarly, for blueberries and
 225 cranberries, we find that the Prairie Provinces depend on interprovincial flows for 83% to 96% of
 226 their supply, Ontario for 75% and Newfoundland & Labrador for 89% of their total supply.
 227 Overall, Canada relies on the United States, Guatemala, Costa Rica, Mexico, and Brazil for 69%
 228 of its total fruit imports.

229 In the case of vegetables, we find that the Canadian provinces rely on international
 230 imports for 37% to 90% of lettuce and chicory and 12% to 83% of cabbage supply. In contrast,
 231 supply of potatoes, onions (except for British Columbia), and carrots and turnips for all
 232 provinces are predominantly domestic (provincial) and interprovincial. The combined domestic
 233 (provincial) and interprovincial supply shares (i.e., Canadian share) are the highest for potatoes
 234 (80% to 100%), followed by carrots and turnips (68% to 100%), and onions (65% to 95%, except
 235 for British Columbia which depends on international imports from Washington). Canadian
 236 provinces source tomatoes fairly equally internationally and from within Canada. Note that our
 237 supply estimates include any processed fruit or vegetable commodities (such as canned tomatoes
 238 or pasta sauce) by converting them back to primary equivalent. This may be why we observe
 239 substantial international supply of tomatoes in our results, despite the large national production.
 240 Taken together, Canada sources 96% of its internationally supplied vegetables from just five
 241 countries: the United States, Mexico, Italy, China, and Peru—with the United States alone
 242 accounting for 67% of that total.

243 We also observe regional preferences in international sourcing regions across western
 244 and eastern provinces (Figure S10). The western provinces dominantly source bananas from
 245 Guatemala and Ecuador, oranges from California, watermelons from Mexico and California, and
 246 apples from Washington. The eastern provinces, however, source larger share of bananas from
 247 Guatemala and Costa Rica, oranges from Brazil, watermelons from Florida and Mexico, and
 248 apples from China.

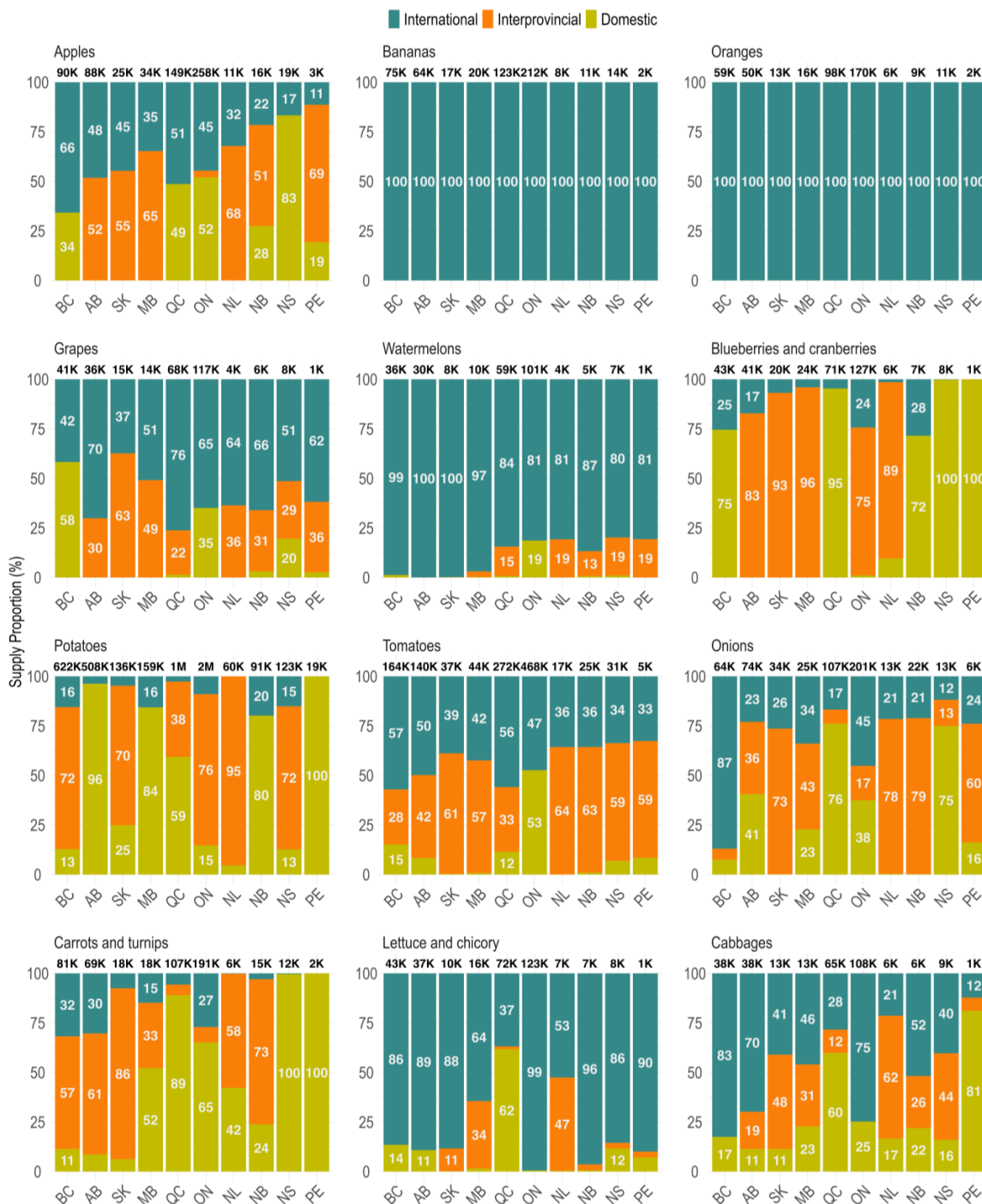




Figure 1. Fruit and vegetable supply to Canadian provinces. Bars show the estimated share of average 2018–2022 provincial supply for consumption from international sources, other Canadian provinces, and within-province production for selected fruits and vegetables. Provinces are BC, British Columbia; AB, Alberta; SK, Saskatchewan; MB, Manitoba; QC, Quebec; ON, Ontario; NL, Newfoundland and Labrador; NB, New Brunswick; NS, Nova Scotia; and PE, Prince Edward Island. Values within segments show percentage shares, and values above bars show average quantities. Interprovincial values are modelled allocations rather than observed shipments.

3.2 Projected changes in agroclimatic indicators vary across current sourcing regions

We estimate projected changes in four agroclimatic indicators across Canada’s current sourcing regions (Figure 2). From +1°C to +3°C global mean warming relative to 1850–1899, California, Washington, Mexico, and Brazil are projected to experience 11 to 43 additional growing-season days above 35°C. Mexico and Brazil are also projected to experience a 6% increase in consecutive dry days. These regions contribute substantial shares of several Canadian supplies: California supplies 60% of strawberries, 57% of plums, 56% of spinach, 49% of lettuce, 43% of cauliflower and broccoli, and 43% of peaches and nectarines; Washington supplies 49% of cherries and 28% of pears; Mexico supplies 94% of avocados, 61% of papayas, 55% of asparagus, 53% of raspberries, 45% of eggplants, and 40% of chillies and peppers; and Brazil supplies 46% of oranges, 38% of papayas, and 29% of cantaloupes and melons.

Canadian fruit and vegetable supply is also linked to sourcing regions with both decreases and increases in maximum five-day rainfall. Guatemala supplies 40% of bananas and 25% of cantaloupes and melons, while Costa Rica supplies 74% of pineapples and 22% of bananas; these regions are projected to experience 8% to 21% decreases in maximum five-day rainfall during the growing season. In contrast, Ecuador, Colombia, and Peru are projected to experience increases of 5% to 9%. Ecuador and Colombia supply 12% and 11% of Canada’s bananas, respectively, and Peru supplies 16% of asparagus.

Within Canada, Ontario, Quebec, and British Columbia are projected to experience 9 to 11 fewer growing-season days below 0°C. Ontario contributes 48% of peas, 45% of tomatoes, 37% of pumpkins, 28% of carrots and turnips, 25% of peaches and nectarines, 23% of grapes, 22% of chillies and peppers, and 21% of apples to national supply. Quebec contributes 43% of blueberries and cranberries, 35% of onions, 25% of peas, 25% of cauliflower and broccoli, and 23% of carrots and turnips.



282 Approximately 43% of fruit supply and 19% of vegetable supply are sourced from
283 regions projected to experience at least 15 additional days above 35°C. Meanwhile, 19% of fruit
284 supply and 8% of vegetable supply are sourced from regions projected to experience at least a
285 five-day increase in consecutive dry days. In contrast, 31% of fruit supply and 9% of vegetable
286 supply are linked to at least a 5% decrease in maximum five-day rainfall, while 7% of fruit
287 supply and 2% of vegetable supply are linked to at least 10 fewer days below 0°C.
288

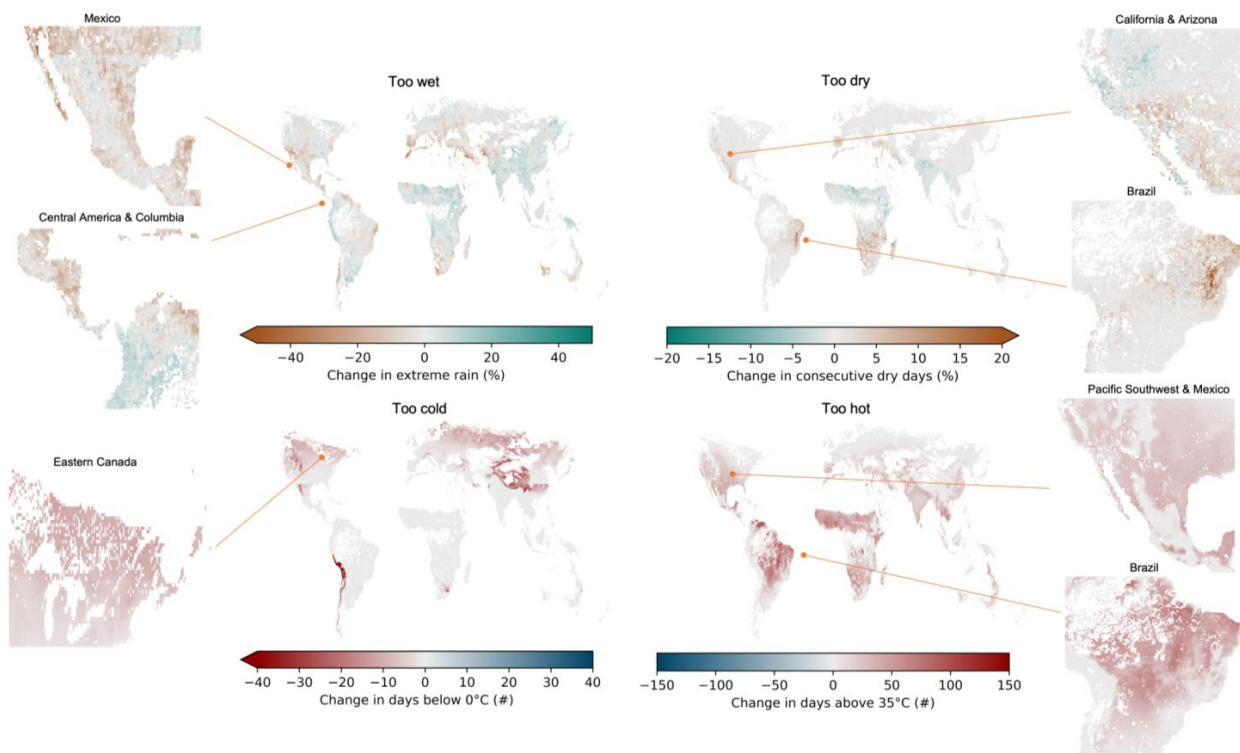




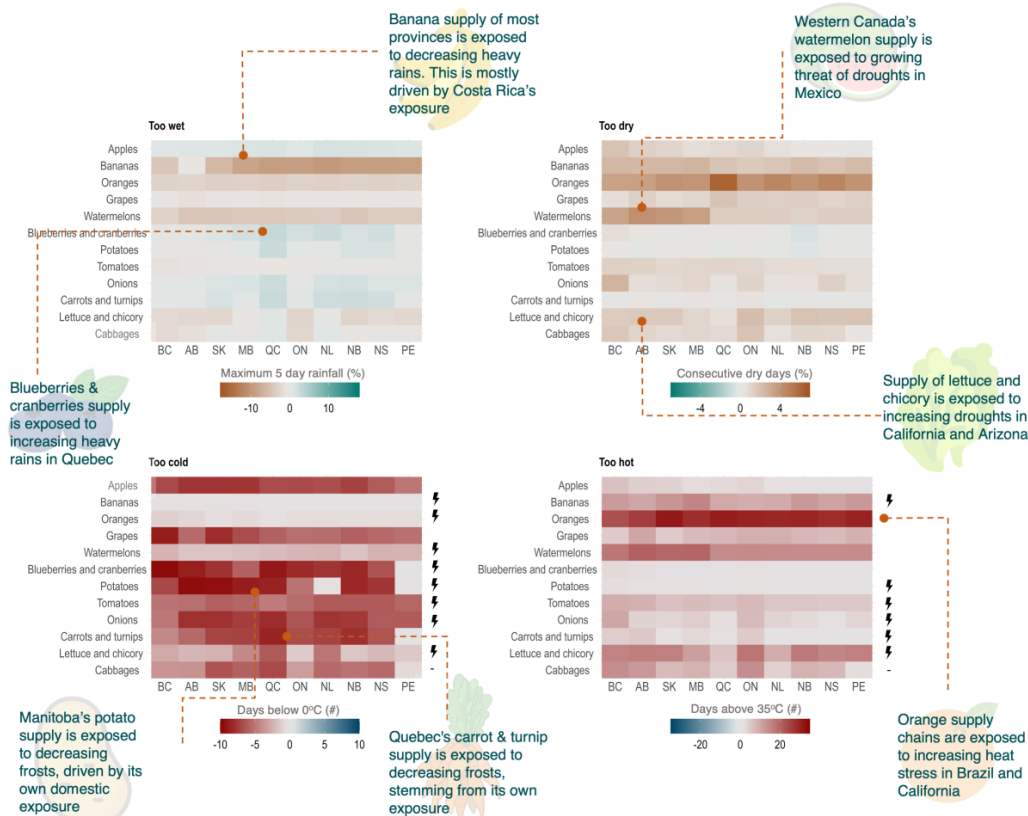
Figure 2 | Projected changes in agroclimatic indicators over global cropland. Maps show changes from +1°C to +3°C global mean warming relative to 1850–1899 during the simplified growing season. Indicators are maximum five-day rainfall (%), consecutive dry days with less than 1 mm rainfall (%), days with minimum temperature below 0°C (number of days), and days with maximum temperature above 35°C (number of days). Values are ensemble medians from nine CMIP6 simulations under SSP2-4.5 selected using the transient climate response criterion. Insets show major regions supplying Canada’s fruits and vegetables.

3.3 Consumption-based exposure varies by commodity, province, and sourcing region

We summarize exposure in two ways. First, for each commodity and province, consumption-based exposure is the weighted average across all Canadian and international sourcing regions, using their contributions to provincial supply (Figure 3; Figures S11–S14). Second, for Canada as a whole, we separate the domestic or within-Canada and cross-border components for each commodity (Figure 4; Figures S13–S14). Cross-border exposure is weighted across international sourcing regions, while domestic exposure is weighted across Canadian sourcing regions. Their combined contributions form overall national consumption-based exposure.

Most fruit and vegetable supplies are linked to an increase or decrease in at least one agroclimatic indicator (Figure 3). Watermelon and lettuce and chicory supplied to western and Atlantic provinces are exposed to increasing dry spells and days above 35°C, primarily because of sourcing from California, Arizona, and Mexico (Figures 3 and 4). Orange supply in all provinces is exposed to increasing dry spells and days above 35°C, driven mainly by sourcing from California and Brazil. Avocado supply, sourced predominantly from Mexico, is likewise exposed to increases in these two indicators (Figure S12).

Other commodities are linked to decreases in particular indicators. Banana supply, especially to eastern provinces, is exposed to decreasing maximum five-day rainfall because of sourcing from Guatemala and Costa Rica (Figure 4; Figure S10). Apples, blueberries and cranberries, carrots and turnips, onions, and potatoes are linked to fewer days below 0°C in major Canadian sourcing regions, including British Columbia, Quebec, Ontario, Prince Edward Island, Alberta, Manitoba, and New Brunswick. These provinces produce a substantial proportion of these fruits and vegetables consumed by Canadians. (Figure S10). These directional changes should not be interpreted as crop-specific benefits without considering sensitivity and timing.



322

323 Figure 3 | Consumption-based exposure of Canadian provincial produce supply. Heatmaps show exposure
324 for selected fruits and vegetables using average 2018–2022 sourcing patterns and changes from +1°C to
325 +3°C global mean warming relative to 1850–1899. Provinces are BC, British Columbia; AB, Alberta; SK,
326 Saskatchewan; MB, Manitoba; QC, Quebec; ON, Ontario; NL, Newfoundland and Labrador; NB, New
327 Brunswick; NS, Nova Scotia; and PE, Prince Edward Island. Values are supply-share-weighted averages
328 across Canadian and international sourcing regions. Symbols on the second y-axis indicate commodities
329 identified in Table S1 as having high expected sensitivity to the temperature indicators.



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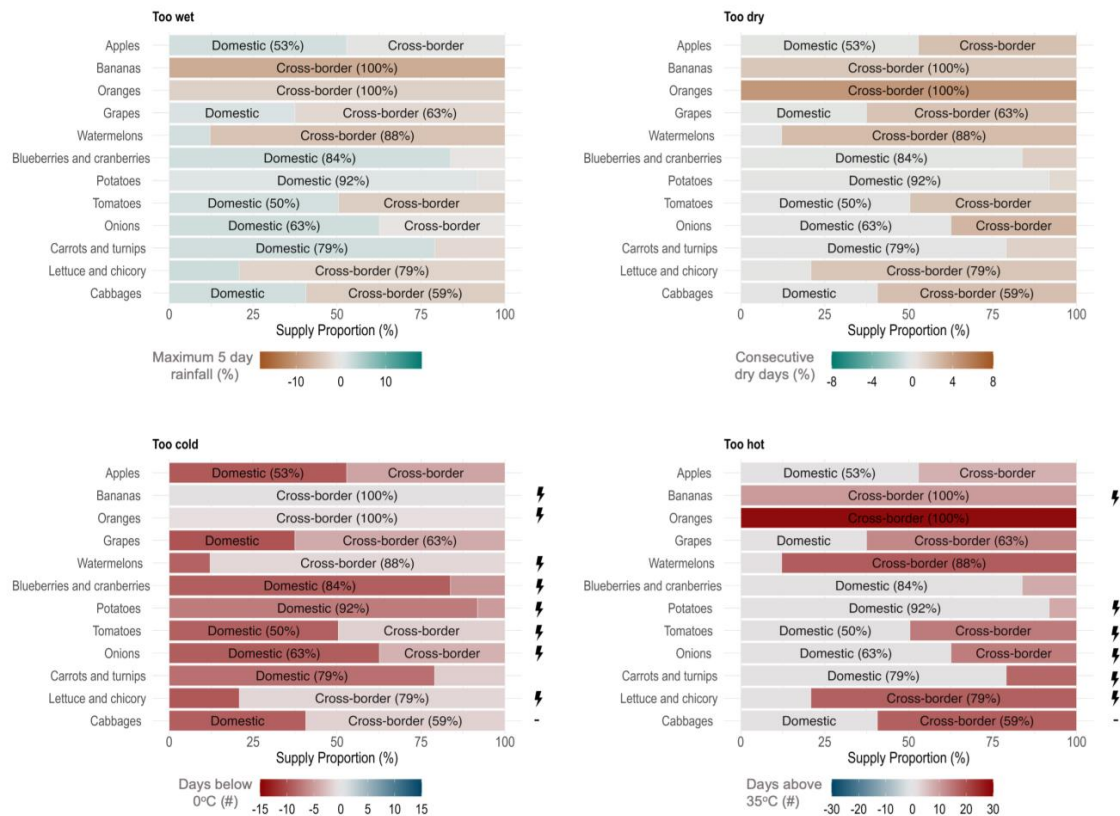


Figure 4 | Within-Canada and cross-border exposure of Canadian national fruit and vegetable supply. Bars separate the contributions of Canadian and international sourcing regions to national exposure for selected commodities, using average 2018–2022 food flows and changes from +1°C to +3°C global mean warming relative to 1850–1899. Colours indicate the magnitude and direction of each agroclimatic indicator. Cross-border exposure is weighted by international sourcing shares, and within-Canada exposure is weighted by Canadian sourcing shares. Where a commodity has no Canadian production contribution, the within-Canada component is assigned zero weight; this does not imply zero overall exposure. Symbols on the second y-axis indicate commodities identified in Table S1 as having high expected sensitivity to the temperature indicators.

4 Discussion

Canada’s fruit and vegetable supply chains are exposed to worsening agroclimatic conditions in the future. There is already a considerable gap between global fruit and vegetable supply and recommended intake (Mason-D’Croz et al., 2019), and previous studies suggest that



345 environmental and climate change may place additional pressure on production (Alae-Carew et
346 al., 2020; Cammarano et al., 2022; Scheelbeek et al., 2018). Where weather shocks result in
347 supply shortfalls, they may also affect prices and affordability, making fruits and vegetables
348 more difficult to access. These concerns may be particularly relevant for countries such as
349 Canada that rely heavily on international imports and are therefore connected to global market
350 fluctuations and export restrictions (Headey, 2011; Martin & Anderson, 2012). Insufficient
351 consumption of fruits and vegetables is among the leading dietary risk factors for disease
352 globally (Afshin et al., 2019). In Canada, the economic costs associated with inadequate fruit and
353 vegetable consumption have been estimated at approximately \$3.3 billion to \$4.4 billion per year
354 (Ekwaru et al., 2017; Krueger et al., 2017).

355 Globally, numerous policies seek to increase fruit and vegetable consumption. Prominent
356 strategies include providing healthy food options in public institutions and implementing public-
357 awareness programs intended to encourage behavioural change (Mason-D'Croz et al., 2019).
358 However, for countries such as Canada that rely substantially on international imports to meet
359 demand for nutrient-rich foods, strategies focused solely on national food environments and
360 consumer behaviour, while important, may not address broader food-system exposure. Systemic
361 perspectives that consider the structure and resilience of supply chains may therefore
362 complement policies designed to support consistent and affordable access to healthy diets.

363 Our results highlight the value of a systemic perspective when assessing climate exposure
364 and considering adaptation policies relevant to food security. First, our food-flow mapping
365 shows that Canadian provinces source most of their fruit and a substantial share of their
366 vegetables through international imports. Canada's exposure to future agroclimatic change
367 therefore extends beyond its national borders to include important production regions in other
368 countries. This provides a rationale for considering cross-border exposure within Canada's
369 international climate and development policies, including support for adaptation and climate
370 resilience in critical supply regions and in low- and middle-income countries more broadly. Such
371 support would also be consistent with Canada's wider responsibilities relating to climate finance,
372 loss and damage, and its historical contribution to climate change. Canada contributed \$2.6
373 billion in international climate finance over five years, of which 24% was allocated to adaptation
374 and 17% to cross-cutting programs (Environment and natural resources, 2022). For context,
375 recovery from the 2021 flooding in British Columbia has been estimated to cost between \$10.6



376 billion and \$17.1 billion (Lee & Parfitt, 2022). Although these figures are not directly
377 comparable, they provide context for the scale of Canada's international adaptation financing
378 relative to the potential costs of major climate-related disasters within Canada.

379 Second, our results identify projected decreases in wet-spell intensity and cold days for
380 some regions contributing to Canadian fruit and vegetable supply. These changes should not
381 automatically be interpreted as benefits, because their consequences will depend on the crop,
382 location, timing, production system and other environmental conditions. Additionally, it is also
383 important to acknowledge the significant uncertainty inherent in the extreme weather exposure
384 estimates derived from various climate models (Figure S15, showing the global exposure for the
385 5th, 50th and 95th percentiles). Nevertheless, changing temperature conditions may alter the
386 potential for producing some commodities within Canada. Canada's current climate limits the
387 production of many tropical fruits and vegetables largely to greenhouses, while a warming
388 climate may change some production possibilities (The Canadian Press, 2024). Supporting
389 small-scale fruit and vegetable growers and processors throughout Canada could strengthen
390 domestic production capacity and reduce reliance on a limited number of international sourcing
391 regions. However, whether such measures would reduce overall climate exposure would depend
392 on the climatic suitability, productivity, economic viability and adaptation capacity of alternative
393 Canadian production systems.

394 Third, the provincial results also show why subnational resolution matters. Supply
395 portfolios differ among provinces, producing different exposure profiles even for the same
396 commodity. For example, watermelon supplied to western provinces is more exposed to
397 increasing dry spells than watermelon supplied to eastern provinces because western supply
398 relies more heavily on Mexico. Such subnational assessments are particularly relevant in
399 Canada's federal system, where provinces exercise substantial authority over many public-sector
400 responsibilities. Greater transparency and traceability within food supply chains would support
401 more detailed assessment of sourcing concentration, exposure and potential adaptation options at
402 provincial and regional scales. Beyond climate exposure and risk, the sub-national food flow
403 dataset developed here will also support more nuanced assessments of environmental and social
404 impacts, including greenhouse gas emissions, land use, water demand, and forced labour
405 associated with production and distribution.



406 While our study's focus on climate exposure provides important insights, it does not
407 encompass the full spectrum of climate risks or opportunities including the sensitivity of various
408 crops to climate stressors, the vulnerability and resilience of producers and consumers and of
409 supply chains themselves, and the broader societal response to climate change (Reisinger et al.,
410 2020). The overall risk or opportunity would also depend on the adoption of adaptation strategies
411 such as more suitable varieties, changing farm management practices (such as shade cloths,
412 greenhouses, irrigation, tunnels, etc.) or crop switching, among others (Berrang-Ford et al.,
413 2021). To truly capture the impacts of climate change on horticulture, a field that has received
414 less attention compared to staple crops, a more detailed and broader assessment is necessary.
415 While some studies have begun to address this gap by assessing the sensitivity of fruits and
416 vegetables to climate and environmental change (Alae-Carew et al., 2020; Cammarano et al.,
417 2022; Scheelbeek et al., 2018)(Alae-Carew et al., 2020; Cammarano et al., 2022; Scheelbeek et
418 al., 2018), the predominant focus has remained on cereal crops (Davis et al., 2021). Future
419 research, that is beyond the scope of this study, should incorporate comprehensive climate
420 change impact assessments along with economic modeling and adaptation potential to better
421 predict shifts in horticultural supply chains, drawing from methodologies applied to cereal crops
422 (Janssens et al., 2020).

423 A number of caveats can be addressed by future work. First, we assume static or sticky
424 sourcing regions, while in reality the sourcing regions might reorganize under future climate
425 change. Forecasting these changes involves complex socio-economic, cultural, and policy
426 factors, and projecting them reliably into the future remains highly uncertain. Future work could
427 also investigate how Canadian supply chains have reorganized with various historical shocks, to
428 assess such reorganisation and resilience potential. Second, provincial supply is estimated
429 assuming similar dietary preferences across provinces. While we evaluate the sensitivity of our
430 results to differential dietary preferences using sales data, future work can improve the flow
431 estimates by incorporating provincial dietary preferences. However, this depends on access to
432 proprietary sales data or supply chain transparency by the large food suppliers. Third,
433 interprovincial redistribution is allocated using geographic proximity between key cities and
434 therefore does not represent observed logistics, contracts, or commercial networks; more detailed
435 optimization approaches could incorporate costs and regional preferences (Dalin & Conway,
436 2016; Harris et al., 2020; Lin et al., 2019). Fourth, the climate analysis uses general cropland,



437 simplified growing seasons, and common thresholds rather than crop-specific production areas,
438 phenology, and damage thresholds (Gaupp, 2020a; Jackson et al., 2021). This is because the
439 literature on context- and variety-specific extreme weather thresholds is sparse and geospatial
440 maps of crop areas are of higher quality for major cereals but poor for fruits and vegetables
441 (Monfreda et al., 2008). These limitations mean that the results should be used to identify
442 exposure patterns, not to forecast future supply outcomes. Fourth, we did not use fruit or
443 vegetable specific extreme weather indicators. This can be done by using crop-specific growing
444 regions, growing seasons, and extreme weather thresholds, as demonstrated by Gaupp (2020a)
445 and Jackson et al. (2021) for selected crops. However, the literature on context- and variety-
446 specific extreme weather thresholds is sparse and geospatial maps of crop areas are of higher
447 quality for major cereals but poor for fruits and vegetables (Monfreda et al., 2008). Fifth, our
448 analysis did not account for the contracting details among various agents in the supply chain,
449 which can influence take-or-pay arrangements at any stage of the supply chain. Additionally, it
450 overlooked various flexibility measures such as timing of harvest, on-route ripening, duration of
451 produce storage, and access to alternative routes of produce utilization (such as canning,
452 fermenting, etc.), particularly in cases of supply and demand imbalances.

453 The significance of cross-border climate exposure in food systems has grown with the
454 increasing connectivity, complexity, and concentration of global food systems. However, the
455 evaluation of cross-border exposure and risk has received limited attention in national climate
456 assessments. In this paper, we provide preliminary assessment of the exposure of Canada's
457 current fruit and vegetable supply to future changes in agroclimatic indicators under climate
458 change.

459 **Acknowledgments**

460 K. Bajaj was supported by the University of British Columbia's Four-Year Doctoral Fellowship
461 and NSERC Discovery Grant #RGPIN-2017-04648 and #RGPIN-2023-05236. N. Ramankutty
462 was supported by NSERC Discovery Grant #RGPIN-2017-04648 and #RGPIN-2023-05236 and
463 the Canada Research Chairs Program grant #CRC-2021-00053.

464 The authors would like to thank Denyse Landry (Senior Analyst, Food Industry Division, Market
465 and Industry Services Branch, Agriculture and Agri-Food Canada), for sharing data used in the
466 sensitivity analysis of food flows.



467

468 **Competing interests**

469 At least one of the (co-)authors is a member of the editorial board of Land Systems.

470

471 **Data Availability**

472 The food-flow data developed for this study are available on Zenodo (Bajaj & Ramankutty,
 473 2025) and can be explored through an interactive web-based platform at
 474 <https://canadafoodflows.ca/>. The downscaled and bias-corrected CMIP6 data are provided by the
 475 Climate Impact Lab through Microsoft's Planetary Computer. Provincial production data and
 476 provincial trade data are provided by Statistics Canada (Statistics Canada, n.d.-a; Statistics
 477 Canada, 2021). Climate analyses were conducted in Python, and the remaining analyses were
 478 conducted in RStudio. NielsenIQ MarketTrack data used in the sensitivity analysis are
 479 proprietary.

480

481 **Author Contribution**

482 KB conceptualized the study, developed the methodology, curated the data, conducted the
 483 analysis, and led the writing of the manuscript. NR contributed to the conceptualization and
 484 methodology, provided critical feedback on the manuscript, and secured funding. ZM
 485 contributed to the methodology and data curation. PM and HD contributed to the
 486 conceptualization, methodology and provided critical feedback on the manuscript.

487

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