Wheat vs Beef?



BUILDING AN AGRIFOOD STRATEGY FOR A CHANGING CLIMATE[1]

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Abstract

Heat is lowering yields of most major staple crops, but the evidence is spread over dozens of studies. The global loss is real and probably understated. Under high emissions, yields of soybean, cassava, wheat and maize fall by 28-36% by 2100 even after farmers adapt, and new field evidence suggests that crop models understate rice losses by about half. The burden falls unevenly. South Asia and sub-Saharan Africa lose the most per degree of warming, have already lost the most productivity growth, and have the least capacity to absorb the shock; Africa now holds 309 million of the world's 645 million hungry people. Developed economies are hit but cushioned. Losses in the US Plains and southern Europe are partly offset by gains at higher latitudes, by irrigation and capital, and, for exporters, by higher prices.

This paper organizes that evidence for the ten largest staple foods and four animal products (beef, pork, chicken and dairy) and sets out a plan for costing it. It follows the four-part framework of the project's earlier inventory: physical loss, adaptation cost, quality loss and market effects.

Step 1, physical loss against a world without climate change, can be done for most staples with the data we have. Under high emissions (RCP8.5), projected yield losses by 2100, net of adaptation costs, run from 6% for rice to 36% for soybean among the six staples with a projection. Cassava (30%), wheat (28%) and maize (28%) lie in between, and the ranking of those three is within study uncertainty. Wheat's loss is the most certain, while rice's is the most uncertain (from a 59% loss to a 109% gain). Method matters: a temperature-only study puts soybean at −12%. Maize and wheat carry most of the absolute stake, about four-fifths of the calories at risk per degree of warming.

Step 2, the monetary value of the losses and the cost of adapting, is only partly possible. A static first figure puts the value at risk at about USD 47 billion a year per degree of warming for five staples, roughly 1.1% of global agricultural output value. Crop-level adaptation costs cannot yet be estimated, because no production-cost series was among our data.

Step 3, losses from reduced quality, is probably the largest gap. No systematic dataset exists, and the leading yield study leaves nutrient content out. We propose a four-stage method to close the gap, but none of it has been carried out. Evidence for meat and dairy is thin, and three staples (sweet potato, yams, plantain) have none. The paper is a structured starting point that shows where the evidence is strong, where it conflicts and where it is missing.

1. The problem, and how we approach it

Yields fall as it gets hotter. What decision makers need to know is which crops, by how much, and what those costs. Existing headline figures do not answer this. The FAO puts disaster losses to agriculture at about USD 99 billion a year (roughly 4% of agricultural GDP), but that counts every weather event, not only the part made worse by climate change.[2] Human-induced warming has cut the growth of global agricultural total factor productivity by about 21% since 1961, the equivalent of losing seven years of progress, and by 26-34% in warmer regions such as Africa and Latin America.[3] This matters for the future because the OECD-FAO Outlook expects global agricultural output to grow 13% by 2035 mainly through productivity gains, the very channel that warming erodes.

A note on measures. The published estimates use three different yardsticks: loss already caused by warming, sensitivity per degree of warming, and projected change by 2100. They also differ in scenario (moderate or high emissions) and in whether farmer adaptation and its cost are included. They answer different questions, so we keep them apart and never add them; where they disagree we say so.

2. Physical loss against no climate change

All figures are losses relative to a world without climate change. Exhibit 1 gives the overview for the ten staples, ordered by share of global calories. Five findings stand out.

- **The loss has started.** Warming has already cut yields by an estimated 4-6% for maize, wheat, rice and soybean (IPCC-assessed attribution studies; different time windows).[4]
- **Every modelled staple loses more by 2100.** Under high emissions, and net of adaptation costs, the loss is 35.6% for soybean, 29.8% for cassava, 28.2% for wheat, 27.8% for maize, 21.7% for sorghum and 6.0% for rice.[5] Ranks two to four are within the studies' uncertainty and should be read as a tie.
- **Certainty differs.** Wheat has only a 4% chance of a gain; rice has the smallest central loss but the widest range (from a 59% loss to a 109% gain), and adaptation removes about 79% of its projected loss but none of wheat's.[6]
- **The source matters.** For soybean, a temperature-only study gives −11.6% by 2100 against −35.6% when adaptation costs are included, and process-based crop models with assumed adaptation show gains. The spread between methods is itself a result.

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2. FAO, *The Impact of Disasters on Agriculture and Food Security 2025*, FAO, Rome, 2025.

3. Ortiz-Bobea, A. et al., *Anthropogenic climate change has slowed global agricultural productivity growth*, Nature Climate Change 11, 306–312, 2021. https://doi.org/10.1038/s41558-021-01000-1

4. IPCC, *Climate Change 2022: Impacts, Adaptation and Vulnerability, WGII Chapter 5: Food, Fibre and Other Ecosystem Products*, Cambridge University Press, 2022. https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-5/

5. Hultgren, A. et al., *Impacts of climate change on global agriculture accounting for adaptation*, Nature 642, 644–652, 2025. https://doi.org/10.1038/s41586-025-09085-w

6. Hultgren, A. et al., *Impacts of climate change on global agriculture accounting for adaptation*, Nature 642, 644–652, 2025. https://doi.org/10.1038/s41586-025-09085-w

- **Rice is likely worse than the models say.** A meta-analysis of 111 studies finds −3.85% per +1 °C, partly offset by CO_2 (+7.1% per 100 ppm).[7] Field-warming trials across 214 plots, however, show a loss of 8.1% per +1 °C against 3.8% in seven global crop models, because models miss heat damage at flowering (Exhibit 1).[8] Rice's small central loss should be read as a lower bound.
- **Wheat loses yield but may gain land.** Yields fall about 6% per degree,[9] yet the crop's northern boundary may shift more than 100 km poleward per degree, and at +2 °C suitable area could expand 15%, offsetting losses globally.[10] Other models still project production falls of 3-16% by 2071-2100.[11] The gains accrue to high-latitude exporters; the losses to low-latitude importers.
- **Roots, tubers and livestock are the blind spots.** Cassava, the staple of the poorest tenth of people, loses about 40% in sub-Saharan Africa by 2100. Heat stress cuts the production value of beef by about 14% and of dairy by about 5% in the tropics; the 2011-12 US drought cost the beef sector over USD 7 billion, and the US herd is now the smallest since 1961.[12]
- **Demand grows fastest where heat bites hardest.** Per-capita consumption of animal-source foods is projected to rise 6% globally but 24% in lower-middle-income countries by 2034, with India and Southeast Asia driving 39% of global growth.[13] Beef emits about 36 kg CO_2e per 1,000 kcal against 0.4-1.4 for staples.[14]
- **Worst affected is not most emitting.** Staples emit 0.4 to 1.4 kg CO_2e per 1,000 kcal, against 36 for beef. Cassava and soybean combine large projected losses with above-average emissions; rice emits a lot and uses the most water but has the smallest central loss (Exhibit 2).

7. Li, N. et al., *Impacts of future climate change on rice yield based on crop model simulation: a meta-analysis*, Science of The Total Environment 949, 2024. https://www.sciencedirect.com/science/article/abs/pii/S004896972405188X

8. Jian, Y. et al., *Global crop models underestimate rice yield responses to extreme heat*, Science Advances 12, eaed9226, 2026. https://www.pik-potsdam.de/en/news/latest-news/global-crop-models-underestimate-how-rice-responds-to-extreme-heat

9. Zhao, C. et al., *Temperature increase reduces global yields of major crops in four independent estimates*, PNAS 114, 9326–9331, 2017. https://doi.org/10.1073/pnas.1701762114

10. Cong, J. et al., *Potential expansion of wheat planting areas driven by climate warming offsets yield losses and enhances global production*, One Earth, 2026. https://www.sciencedirect.com/science/article/abs/pii/S2590332225002908

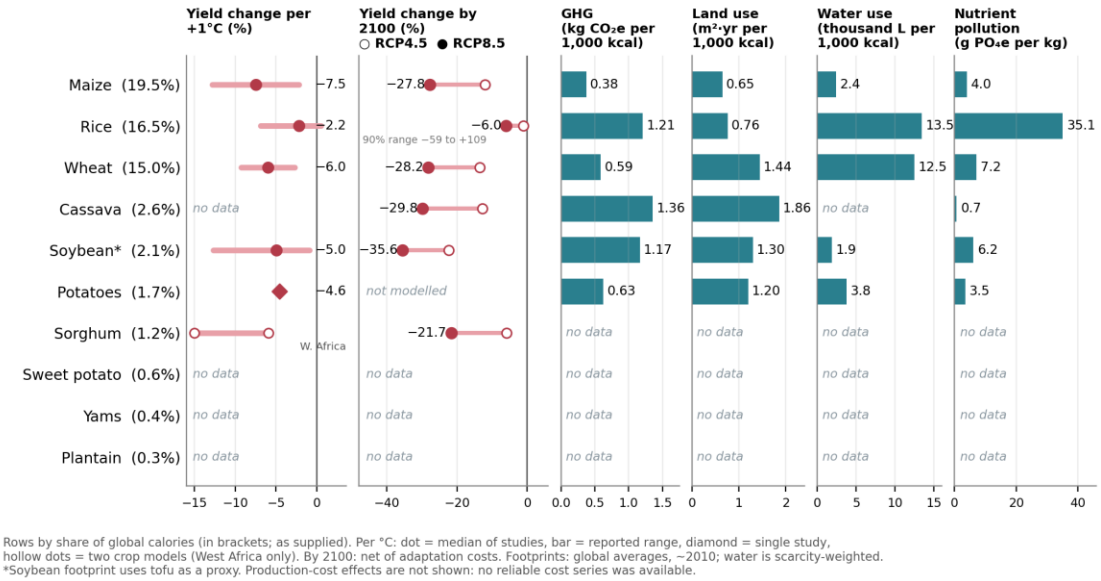
11. Guo, X., Zhang, P. and Yue, Y., *Prediction of global wheat cultivation distribution under climate change and socioeconomic development*, Science of The Total Environment 919, 170481, 2024. https://www.sciencedirect.com/science/article/abs/pii/S0048969724006181

12. Beck, P. A. and Beck, M. R., *Effects of climate change on long-term resilience of beef cattle production*, Applied Animal Science 42(1), 84–94, 2026. https://www.sciencedirect.com/science/article/pii/S2590286525001120

13. OECD/FAO, *OECD-FAO Agricultural Outlook 2025–2034*, OECD Publishing, Paris, 2025. https://www.oecd.org/en/publications/oecd-fao-agricultural-outlook-2025-2034_601276cd-en.html

14. Poore, J. and Nemecek, T., *Reducing food's environmental impacts through producers and consumers*, Science 360, 987–992, 2018 (data via Our World in Data). https://doi.org/10.1126/science.aaq0216

Exhibit 1. Every modelled staple loses yield, but the evidence is uneven across crops

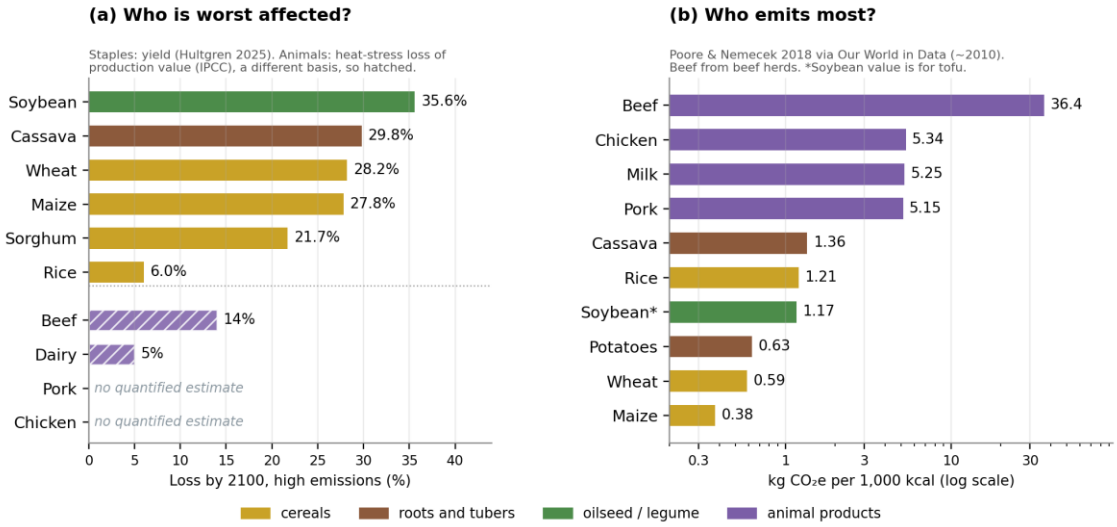


Rows by share of global calories (in brackets; as supplied). Per °C: dot = median of studies, bar = reported range, diamond = single study, hollow dots = two crop models (West Africa only). By 2100: net of adaptation costs. Footprints: global averages, ~2010; water is scarcity-weighted. *Soybean footprint uses tofu as a proxy. Production-cost effects are not shown: no reliable cost series was available.

Note: Overview of the ten staples: yield change per +1 °C and by 2100, and environmental footprint. "No data" marks a gap in the evidence, not a zero.
Source: Zhao et al. (2017); Rezaei et al. (2024); Hultgren et al. (2025); IPCC (2022); Poore and Nemecek (2018) via Our World in Data; Vision analysis.

In absolute terms the picture shifts toward the big crops. Per degree of warming, the five staples with a global estimate (54.8% of global calories) put about 2.9 percentage points of global calories at risk, and maize and wheat account for roughly four-fifths of that. Soybean is hit hard in percentage terms but supplies only 2.1% of calories.

Exhibit 2. The worst-affected staples are not the highest emitters

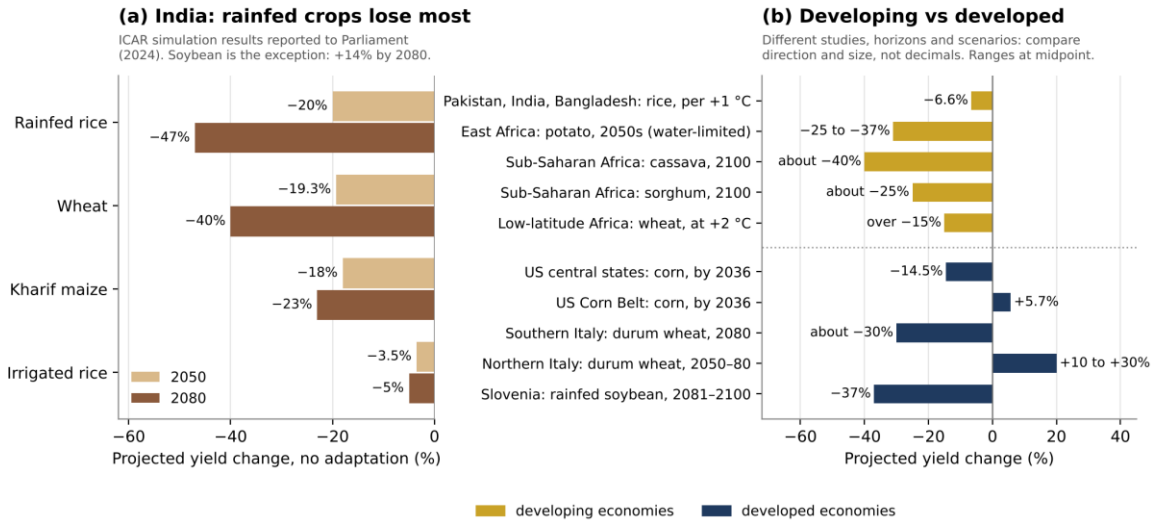


Note: (a) Worst affected: projected loss by 2100 under high emissions (staples: yield; beef and dairy: heat-stress loss of production value, a different basis, so hatched and not ranked). (b) Highest emitting: greenhouse gases per 1,000 kcal, logarithmic scale. * Soybean value is for tofu.
Source: Hultgren et al. (2025); IPCC (2022); Poore and Nemecek (2018) via Our World in Data; Vision analysis.

3. Regional impact: developing and developed economies

The same degree of warming does different damage in different places. Three factors decide it: how close crops already grow to their heat limits, how much farming depends on rain rather than irrigation, and how much capacity a country has to adapt and to import. On all three, developing economies in the tropics are more exposed (Exhibit 3).

Exhibit 3. Rainfed crops in India and staples in Africa face the steepest projected losses



Note: (a) India: projected yield change without adaptation, 2050 and 2080. (b) Selected regional projections in developing and developed economies; studies differ in horizon and scenario.
Source: ICAR, Lok Sabha reply (2024); Jian et al. (2026); Kirina et al. (2025); Hultgren et al. (2025); Zhang et al. (2022); Beckman et al. (2023); Mereu et al. (2021); Barrera et al. (2025); Vision analysis.

India and other countries of South Asia: Simulation studies presented to Parliament of India project that, without adaptation, rainfed rice yields fall 20% by 2050 and 47% by 2080, wheat 19.3% and 40%, and kharif maize 18% and 23%, while irrigated rice loses only 3.5% and 5%; soybean is the exception, gaining up to 14%.[15] A 2026 state-wise panel study finds smaller national rice effects (yield −1.5% by the 2040s and −2.4% by 2100; production −2.4% and −4.3%), driven mainly by evapotranspiration.[16] The gap reflects method and the buffer of irrigation: the risk sits in rainfed eastern and central states. India's exposure is also the world's: it supplies about 40% of global rice exports, and its 2022 wheat export ban after a March heatwave and 2023 curbs on rice exports moved world prices.

Once heat damage at flowering is included, rice losses for a 1°C warming in Pakistan, India and Bangladesh rise from 2.1% to 6.6%, and in Thailand, the Philippines and Myanmar from 3.7% to 7.7%, while China and Japan change by under two points.[17] Rice feeds over 4 billion people and

15. Ministry of Agriculture and Farmers Welfare (ICAR simulations), *Reply to the Lok Sabha on climate impacts on crop yields*, 30 July 2024. https://www.downtoearth.org.in/governance/as-told-to-parliament-july-30-2024-climate-impact-could-reduce-rainfed-rice-yields-by-20-by-2050-and-47-by-2080

16. Singh, R. and Singh, A. K., *Projected impact of climate change on rice production and yield in India: a state-wise panel data empirical analysis*, Indian Journal of Agricultural Research, 2026. https://arccjournals.com/journal/indian-journal-of-agricultural-research/A-6469

17. Jian, Y. et al., *Global crop models underestimate rice yield responses to extreme heat*, Science Advances 12, eaed9226, 2026. https://www.pik-potsdam.de/en/news/latest-news/global-crop-models-underestimate-how-rice-responds-to-extreme-heat

supplies up to 70% of calories in some countries.[18] Undernourishment in Southern Asia fell from 13.9% in 2021 to 9.3% in 2025, driven by India,[19] progress that heat-driven rice and wheat losses directly threaten.

Africa: Climate change has already cut Africa's agricultural productivity growth by 34% since 1961, more than any other region,[20] and sorghum yields in West Africa are already 6-15% lower.[21] By 2100, cassava loses about 40% and sorghum about 25% in sub-Saharan Africa;[22] at +2 °C, wheat yields in low-latitude Africa fall more than 15% while global price spikes worsen.[23] East African potato yields could fall 25-37% by the 2050s, with 82% of currently cultivable land unsuitable by 2050.[24] The starting point is fragile: 20% of Africans are hungry, 56.6% are moderately or severely food insecure, and 66.6% cannot afford a healthy diet.[25]

Developed economies: Losses are real but uneven and cushioned. In the United States, corn yields in the central states fall 14.5% by 2036 (up to 25% in the Plains) while the Corn Belt gains 5.7%; soybean exports fall USD 319 million,[26] and by 2100 the US grain belt loses about 40% of maize. Europe splits north-south: durum wheat gains 10-30% in northern Italy but loses about 30% in the south by 2080, maize loses 33-43%,[27] and Swiss maize projections stay within normal year-to-year variation.[28] Irrigation is a decisive buffer: in Slovenia rainfed soybean falls from 4.3 to 2.7 t/ha by 2081-2100, while irrigated yields reach 6.5 t/ha.[29] Adaptation is affordable but not free: the EEA puts EU agricultural needs at EUR 7-8 billion a year to 2050 under moderate emissions and EUR 11-17 billion under high.[30]

4. What the losses are worth, and what adapting costs

What we can say now. Multiplying each crop's per-degree loss by its production value (FAOSTAT, 2021-23, constant 2014-16 dollars)[31] gives a first monetary figure: about USD 47 billion a year per degree of warming for the five staples, roughly 1.1% of global agricultural output value. Maize (17.9) and wheat (11.3) lead, followed by soybean (6.9), rice (6.8) and potatoes (4.4).

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18. World Economic Forum, *How much is a bowl of rice? Food security and climate change*, 15 October 2025. https://www.weforum.org/stories/food-water-air/how-much-is-a-bowl-of-rice-food-security-climate-change/

19. FAO, IFAD, UNICEF, WFP and WHO, *The State of Food Security and Nutrition in the World 2026*, FAO, Rome, 2026. https://wfpusa.org/news/un-report-global-hunger-levels-ease-for-third-consecutive-year-as-regional-disparities-persist/

20. IPCC, *Climate Change 2022: Impacts, Adaptation and Vulnerability, WGII Chapter 9: Africa*, Cambridge University Press, 2022. https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-9/

21. Sultan, B., Defrance, D. and Iizumi, T., *Evidence of crop production losses in West Africa due to historical global warming in two crop models*, Scientific Reports 9, 12834, 2019.

22. Hultgren, A. et al., *Impacts of climate change on global agriculture accounting for adaptation*, Nature 642, 644–652, 2025. https://doi.org/10.1038/s41586-025-09085-w

23. Zhang, T. et al., *Increased wheat price spikes and larger economic inequality with 2 °C global warming*, One Earth 5(8), 2022. https://cordis.europa.eu/article/id/442076-how-will-climate-change-affect-the-yield-and-price-of-wheat

24. Kirina, T. et al., *Projected climate change impacts on potato yield in East Africa*, European Journal of Agronomy, 2025. https://www.sciencedirect.com/science/article/pii/S1161030125000565

25. FAO, IFAD, UNICEF, WFP and WHO, *The State of Food Security and Nutrition in the World 2026*, FAO, Rome, 2026. https://wfpusa.org/news/un-report-global-hunger-levels-ease-for-third-consecutive-year-as-regional-disparities-persist/

26. Beckman, J., Ivanic, M. and Nava, N., *Estimating Market Implications From Corn and Soybean Yields Under Climate Change in the United States*, USDA ERS, ERR-324, 2023. https://www.ers.usda.gov/amber-waves/2024/march/ers-research-models-future-effects-of-climate-change-on-corn-and-soybean-yields-production-and-exports

27. Mereu, V. et al., *Modeling high-resolution climate change impacts on wheat and maize in Italy*, Climate Risk Management 33, 100339, 2021. https://www.sciencedirect.com/science/article/pii/S2212096321000681

28. Holzkämper, A. et al., *Projecting climate change impacts on grain maize based on three different crop model approaches*, Agricultural and Forest Meteorology 214–215, 219–230, 2015. https://www.sciencedirect.com/science/article/abs/pii/S016819231500698X

29. Barrera, W. et al., *Projecting the impacts of climate change on soybean production and water requirements using AquaCrop model*, European Journal of Agronomy, 2025. https://www.sciencedirect.com/science/article/pii/S1161030125000346

30. European Environment Agency, *Adaptation investment needs for European agriculture (as cited in the project inventory)*, 2025.

31. FAO, *FAOSTAT: Value of Agricultural Production*, 2021–23 data, constant 2014–16 international dollars. https://www.fao.org/faostat/en/

This is a static estimate: it ignores price responses, adaptation and substitution between crops. On adaptation, the leading study reports yields net of adaptation costs and finds that adaptation and income growth offset about a quarter of the global calorie loss by 2050 and a third by 2100, unevenly across crops and regions.[32] For agriculture as a whole, the IPCC reports that climate change has cut the growth of total factor productivity (output per unit of all inputs) by a cumulative 21% since 1961, and by 30-33% in Africa and Latin America.[33]

What is missing. No dollar figure for the cost of adapting, crop by crop. Production-cost series exist mainly for the United States (USDA), and none was among our data.

How we will do it. First, value the physical loss at farm-gate prices, by country, against the no-climate-change output. Second, measure adaptation cost as the change in real operating cost per tonne within consistent survey series (USDA cost accounts; EU farm accountancy data and national budgets elsewhere), taking care that USDA updates costs between surveys with price indices, so only survey-to-survey changes reflect practice. Third, add losses and adaptation costs but keep price effects separate. For meat and dairy, add the feed channel: feed share of production cost times the cost change of feed crops, since maize and soybean feed the animals.

Losses also do not stay where they fall. At +2 °C the global wheat price rises only 1.8% on average, but the 95th percentile of price spikes rises 6.2%, and the burden falls on low-income importers.[34] Trade is the main shock absorber, with 22% of calories expected to cross borders by 2034, but the 2026 Middle East conflict is already constraining fertiliser use and cereal output in low-income countries.[35] The scale is easiest to see against trend growth: cereal yields are projected to rise about 0.9% a year, so a loss of 4-8% per degree erases roughly four to nine years of yield gains. Hunger fell to 645 million in 2025 (7.8%), and SOFI projects 510-520 million by 2030, a projection that excludes a possible 2026-27 El Niño.[36]

5. Losses from reduced quality

Warming changes what is harvested, not only how much. Produce comes out smaller or lower grade (undersized potatoes in Europe's 2026 drought),[37] with altered composition (grape sugar and acidity, and so wine quality), and, under higher CO_2, with lower protein and micronutrient content. Yields can look stable while value falls. This is probably the largest cost we are missing: no systematic global dataset exists, the leading yield study explicitly leaves nutrient content out, and

32. Hultgren, A. et al., *Impacts of climate change on global agriculture accounting for adaptation*, Nature 642, 644–652, 2025. https://doi.org/10.1038/s41586-025-09085-w

33. IPCC, *Climate Change 2022: Impacts, Adaptation and Vulnerability, WGII Chapter 5: Food, Fibre and Other Ecosystem Products*, Cambridge University Press, 2022. https://www.ipcc.ch/report/ar6/wg2/chapter/chapter-5/

34. Zhang, T. et al., *Increased wheat price spikes and larger economic inequality with 2 °C global warming*, One Earth 5(8), 2022. https://cordis.europa.eu/article/id/442076-how-will-climate-change-affect-the-yield-and-price-of-wheat

35. OECD/FAO, *OECD-FAO Agricultural Outlook 2026–2035*, OECD Publishing, Paris, 2026. https://www.oecd.org/en/publications/oecd-fao-agricultural-outlook-2026-2035_47874669-en.html

36. FAO, IFAD, UNICEF, WFP and WHO, *The State of Food Security and Nutrition in the World 2026*, FAO, Rome, 2026. https://wfpusa.org/news/un-report-global-hunger-levels-ease-for-third-consecutive-year-as-regional-disparities-persist/

37. Energy & Climate Intelligence Unit, *Impact of the 2026 summer drought and heatwaves on the European potato harvest*, 2026. https://eciu.net/analysis/reports/potato-harvest

it is therefore absent from every figure above. It is part of the goal, and we propose to approach it in four stages.

- **Pick the quality measure that sets the price** for each crop: size class for potatoes, protein for wheat, sugar and acidity for wine grapes, bean size and defects for coffee and cocoa.
- **Collect price differences between grades** from national grading statistics and market data, to know what a downgrade costs.
- **Link quality to climate** using field-warming and elevated-CO_2 experiments and regional grading records compared with a trend, to estimate the share of output downgraded per degree.
- **Value it and report it separately:** downgraded share times price discount, shown next to the yield loss. Nutrient dilution is reported in nutritional terms (protein, zinc, iron per hectare), not dollars.

We would start where quality visibly drives price (wine grapes, coffee, cocoa, potatoes) and with wheat protein. These stages are a plan; none has been carried out.

6. Limits and next steps

Calorie shares are as supplied, and maize's 19.5% may include animal feed, which would overlap the feed channel. Evidence for meat and dairy is thin: one projected heat-stress loss each for beef (about 14% of production value) and dairy (about 5%), none for pork or chicken. Sweet potato, yams and plantain have no evidence at all, and only six staples have a projection to 2100. The next steps are the ones above: obtain cost data to complete Step 2, and build the quality dataset for Step 3. A fuller model with price responses would be better still; this paper is a structured starting point that shows where the evidence is strong, where it conflicts and where it is missing.

Appendix

Exhibit 4. Climate exposure and footprint: staples, meat and dairy, and other products

What the evidence we hold says for each good. A row appears only where there is data behind it. Numbers in different columns measure different things and should not be added or ranked against each other.

Good	Why included	Output change per +1°C of warming	Observed to date, or documented events	Projected change by 2100 (high emissions; moderate in brackets)	Cost change	GHG, kg CO_2e per 1,000 kcal (per kg)	Land · water · nutrient pollution*	Key caveat	Source
Ten most important staples (by share of global calories, as supplied)									
Maize 19.5% of calories	Top-10 staple ★	**−7.4%** (95% CI −11.9 to −2.9) −7.5% in the larger review	**−5.9%** (1961-2017) −4.1% (1981-2010)	**−27.8%** (−12.0%)	Producer price +20% by 2050 (mean, four major crops) *AgMIP global model ensemble* 2012: record USD 8.17/bu, +50% in five weeks *2012 US Midwest drought*	0.38 (1.70)	0.65 · 2.4 · 4.0	Strongest temperature evidence. US grain belt about −40%. The 19.5% share may include animal feed.	Zhao 2017; Rezaei 2024; Hultgren 2025; IPCC; OWID; Nelson 2014; CNN 2012

Good	Why included	Output change per +1°C of warming	Observed to date, or documented events	Projected change by 2100 (high emissions; moderate in brackets)	Cost change	GHG, kg CO_2e per 1,000 kcal (per kg)	Land · water · nutrient pollution*	Key caveat	Source
Rice 16.5% of calories	Top-10 staple	**−3.2%** (95% CI −6.9 to +0.5) −1.2% in the larger review	**−4.2%** (1961-2017)	**−6.0%** (−1.1%) 90% range −59% to +109%	Producer price +20% by 2050 (mean, four major crops) *AgMIP global model ensemble* FAO rice price index +9.8% in one month, 15-year high (Aug 2023) *India export ban, El Niño*	1.21 (4.45)	0.76 · 13.5 · 35.1	Smallest central loss, widest uncertainty. Adaptation removes about 79% of the loss. Highest water and nutrient footprint.	Zhao 2017; Hultgren 2025; IPCC; OWID; Nelson 2014; FAO 2023
Wheat 15.0% of calories	Top-10 staple ★	**−6.0%** (95% CI −8.9 to −3.1) −6.0% in the larger review	**−4.9%** (1961-2017)	**−28.2%** (−13.5%)	Mean world price +1.8%; price spikes (95th pct.) +6.2% at +2 °C *Climate-wheat-economic model ensemble* Producer price +20% by 2050 (mean, four major crops) *AgMIP global model ensemble*	0.59 (1.57)	1.44 · 12.5 · 7.2	Most certain loss (4% chance of a gain). Adaptation does not reduce wheat losses. Footprint is for wheat and rye.	Zhao 2017; Rezaei 2024; Hultgren 2025; IPCC; OWID; Zhang 2022; Nelson 2014
Cassava 2.6% of calories	Top-10 staple	*No global estimate*	*No global estimate*	**−29.8%** (−12.8%)	*No reliable data*	1.36 (1.32)	1.86 · n/a · 0.7	One study only. Sub-Saharan Africa about −40%. The lowest-income tenth of people depends on it.	Hultgren 2025; OWID
Soybean 2.1% of calories	Top-10 staple ★	−3.1% (not significant) to −6.8% The two sources disagree	**−4.5%** (1981-2010)	**−35.6%** (−22.4%)	2012: record USD 16.90/bu, +25% in six weeks *2012 US Midwest drought* US exports −USD 319m a year by 2036 *USDA climate yield projection*	1.17 (3.16)†	1.30 · 1.9 · 6.2†	Largest projected loss, yet a temperature-only study gives only −11.6%. US about −50%, wet Brazil about +20%.	Zhao 2017; Rezaei 2024; Hultgren 2025; IPCC; OWID; CNN 2012; Beckman 2023
Potatoes 1.7% of calories	Top-10 staple	−4.6% (single study)	No global estimate. *Event:* 2026 drought and heat cut Europe's harvest by about 3.1 Mt (4 countries); EUR 498-818m of lost production across 5 countries	*Not modelled by Hultgren* −2 to −6% by 2055 (IPCC)	EUR 498-818m of production value lost (5 countries) *2026 European drought, heatwaves*	0.63 (0.46)	1.20 · 3.8 · 3.5	Single-study evidence; large regional spread. The 2026 event has no formal attribution yet.	IPCC (Fleisher 2017; Raymundo 2018); ECIU 2026; OWID
Sorghum 1.2% of calories	Top-10 staple	*No global estimate* West Africa only: −5.9% to −15.0%	−5.9% to −15.0% (West Africa, 2000-09, two crop models)	**−21.7%** (−5.9%)	*No reliable data*	*No data*	*No data*	North America about −40%, Sub-Saharan Africa about −25%. Regional figures are not scaled to the world.	Sultan 2019; Hultgren 2025
Sweet potato · Yams · Plantain 0.6% · 0.4% · 0.3% of calories	Top-10 staples	*No data*	*No data*	*No data*	*No reliable data*	*No data*	*No data*	Not covered by any study we hold.	—

Good	Why included	Output change per +1°C of warming	Observed to date, or documented events	Projected change by 2100 (high emissions; moderate in brackets)	Cost change	GHG, kg CO_2e per 1,000 kcal (per kg)	Land · water · nutrient pollution*	Key caveat	Source
Meat and dairy									
Beef USD 275 bn value	Meat and dairy	*No quantified estimate*	*No quantified estimate (IPCC: evidence limited)*	**−14%** of production value (heat stress, tropics and subtropics; high emissions) Single study	USD 30.8bn a year lost by 2100 (14.4% of value) *Global heat-stress model, SSP5-8.5* US: at least USD 369m a year; 2011-12 drought cost over USD 7bn *US heat stress and drought*	**36.4** (99.5) dairy-herd beef 12.2 (33.3)	*No data*	Feed intake falls 3-5% per °C above the comfort zone. The feed-price effect on cost is not estimated.	IPCC; OWID; Thornton 2022; St-Pierre 2003; Beck 2026
Pork USD 238 bn value	Meat and dairy	*No quantified estimate*	*No quantified estimate*	*No quantified estimate (IPCC: pigs hit in mid-latitudes)*	US: at least USD 299m a year *US livestock heat-stress estimate*	5.15 (12.31)	*No data*	Only a qualitative IPCC statement.	IPCC; OWID; St-Pierre 2003
Chicken USD 232 bn value	Meat and dairy	*No quantified estimate*	*No quantified estimate*	*No quantified estimate (IPCC: more heat-stress days)*	US poultry: at least USD 128m a year *US livestock heat-stress estimate*	5.34 (9.87)	*No data*	Only a qualitative IPCC statement.	IPCC; OWID; St-Pierre 2003
Dairy (milk) USD 321 bn value	Meat and dairy	*No estimate*	About 1% of annual milk yield lost to heat, US sample of 18,000 herds, 2012-16 (USD 245m over five years)	**−5%** of production value (heat stress; high emissions) Milk yield −1% to −17% in parts of USA, UK, West Africa	USD 9.1bn a year lost by 2100 (4.7% of value) *Global heat-stress model, SSP5-8.5* US: at least USD 897m a year *US livestock heat-stress estimate*	**5.25** (3.15) cheese 6.17	*No data*	The US study shows a mechanism, not an attributed 2021-26 loss.	IPCC; Food Policy 2025; OWID; Thornton 2022; St-Pierre 2003
Other products from the project inventory (only those with data)									
Coffee USD 23 bn value	Project inventory	*No estimate*	*Events:* Vietnam output −20% and Indonesia −16.5% (2023/24); Brazil forecast cut from +5.5% to −1.6%. World price +38.8% in 2024	*No projection*	Arabica above USD 4.30/lb (Feb 2025), +70% in 2024 *Brazil drought, low stocks*	50.9 (28.5)‡	*No data*	FAO calls weather the main supply-side driver; the share due to climate change is not established.	FAO 2025; OWID; Perfect Daily Grind 2025
Cocoa USD 8 bn value	Project inventory	*No estimate*	*Attribution:* at least 3 extra weeks a year above 32°C in Côte d'Ivoire and Ghana over a decade; about 6 extra weeks in 71% of cocoa areas in 2024	*No projection*	Record USD 12,200/t (Apr 2024), over 3× April 2022 *West African rains, heat, disease*	9.0 (46.7)†	*No data*	Strong for extra heat, weaker for tonnes and prices. Footprint is for dark chocolate, not beans.	Climate Central 2025; OWID; ECIU 2025
Olive oil USD 23 bn (olives)	Project inventory	*No estimate*	*Event:* world output 2.56 Mt in 2023/24 (−7%), then 3.38 Mt in 2024/25 (+32%)	**−14.9%** maximum yield loss, 2041-70, Mediterranean, hot-dry scenario	Wholesale EUR 7.35-9.00/kg, over 2× 23-year high (2023) *Mediterranean drought and heat 2022-23*	0.61 (n/a)	*No data*	Output swings are not climate-only. Projection is a single-study maximum. Almond (−27%) in same study.	IPCC (Valverde 2015); IOC 2024; OWID; Sci. Am. 2023
Wine grapes USD 66 bn (grapes)	Project inventory	*No estimate*	Harvests advanced about 2-3 weeks over 40 years; heat alters grape composition and wine quality	**−5.4%** maximum yield loss, 2041-70, Mediterranean, hot-dry scenario	*No reliable data*	2.68 (1.53)†	*No data*	Yield only: the effect on grape composition and wine quality is not quantified.	IPCC (Valverde 2015); Nat. Rev. Earth Env. 2024; OWID

Good	Why included	Output change per +1°C of warming	Observed to date, or documented events	Projected change by 2100 (high emissions; moderate in brackets)	Cost change	GHG, kg CO_2e per 1,000 kcal (per kg)	Land · water · nutrient pollution*	Key caveat	Source
Marine fisheries	Project inventory	−5% of marine animal biomass per +1°C (model-based)	Marine heatwaves hit about 15% of fisheries (1985-2022): over 5.6 Mt lost, USD 6.6 bn (3.9 bn in 2013-22) Maximum sustainable yield −4.1% (1930-2010)	Biomass −5% (moderate) to −17% (high) by 2100 Catch potential −5% to −7% by 2050	Single heatwave events: over USD 800m direct losses each *Review of 34 marine heatwaves*	*No data (source covers only farmed fish)*	*No data*	Biomass is not catch. The heatwave loss is not a pure climate attribution.	IPCC; FAO 2025; Smith 2021

Notes

- ★ Soybean (rank 1), wheat (rank 3) and maize (rank 4) are the three worst-affected goods with the most data, ranked by projected loss by 2100 (Hultgren et al. 2025). Cassava (rank 2) and sorghum (rank 5) have too little data to include in the three. All five are already among the ten staples, so they are marked rather than repeated.
- **Measures.** Per °C: effect of warming alone (no adaptation or CO_2 fertilization). By 2100: yield net of adaptation costs, high emissions (RCP8.5), moderate emissions in brackets; for animal products and perennial crops, the single studies named. Observed: loss attributed to human-induced warming against a no-warming counterfactual, with the window in brackets. **Events** and price changes are not attributed to climate change unless marked "attribution".
- **Cost.** No crop-level production-cost series was available, so this column gives the closest evidence (event price moves, modelled price effects, heat-stress loss values), with background in italics. These are not attributed costs and are not added to yield losses. Warming expected by 2035 adds 0.92-3.23 percentage points a year to food inflation (Kotz et al. 2024). Yield figures by 2100 are already net of adaptation costs.
- **Proxies.** Soybean uses tofu, cocoa uses dark chocolate, wine grapes use berries and grapes combined. For coffee, emissions per 1,000 kcal are not a meaningful basis; per kilogram it is 28.5. *Footprint columns: land in m^2·year per 1,000 kcal; water in thousand litres per 1,000 kcal, scarcity-weighted; nutrient pollution (eutrophication) in g PO_4e per kg. Global averages, reference year about 2010; water and nutrient figures exist only for the staples. Production values are FAOSTAT gross values (2021-23, constant 2014-16 international dollars).
- **Not shown as a row.** European agriculture as a whole is an aggregate, not a product: the European Environment Agency puts adaptation investment needs at EUR 7-8 bn a year to 2050 under moderate emissions and EUR 11-17 bn under high. Pork and chicken are kept despite having no quantified climate effect, because they belong to the meat group and have footprint data.

Source: Hultgren et al. (2025); Zhao et al. (2017); Sultan et al. (2019); IPCC (2022); Rezaei et al. (2024); Poore and Nemecek (2018) via Our World in Data; FAOSTAT; FAO (2025); Climate Central (2025); IOC (2024); ECIU (2025, 2026); Food Policy (2025); Nat. Rev. Earth Environ. (2024); Nelson et al. (2014); Thornton et al. (2022); St-Pierre et al. (2003); Beck and Beck (2026); Beckman et al. (2023); Zhang et al. (2022); Kotz et al. (2024); CNN Money (2012); FAO via AFP (2023); Perfect Daily Grind (2025); Scientific American (2023); Smith et al. (2021); Vision analysis.

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