Climate Resilient School Meals

A report by the Center on Food Security and the Environment

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We are grateful to the program staff from a number of school feeding programs who spoke with us and gave us a deeper understanding of the procurement challenges faced by individual programs.

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Abstract: School feeding programs are an increasingly important and cost-effective nutritional backstop in a majority of countries, but the climate resilience of this social safety net is not well-characterized. In particular, status quo procurement policies, including food purchased via international markets or acquired through bilateral trade or aid agreements, may be inadvertently exposing school feeding programs and the children that depend on them to climate risk (domestically or abroad), associated price volatility, and larger-scale regional shocks that could collapse programs. Here we present the first systematic empirical study of climate risk to school feeding programs, taking into account the composition of school meals, where procured food is grown, and how it is produced and acquired. This analysis provides both baseline vulnerability assessments for individual school feeding programs and larger-scale characterization of risk and opportunity in the school meals social safety net as a whole. Through simple scenario analyses and case studies, we also explore opportunities for resilience through procurement policies, including requiring more climate-resilient methods of food production (i.e., regenerative agriculture) and options for purchasing domestic versus internationally traded products.

Background and Motivation

Children around the world are vulnerable to malnutrition over short time scales, with lifelong consequences.[1–4] Because child and adolescent nutrition strongly influence longer-run human capital formation and economic development, governments around the world have increased investment into school feeding programs as a growing component of social safety nets.[5–7] School feeding programs have also come to be seen as potential policy levers for achieving goals beyond improved childhood nutrition, school attendance, and educational attainment. As large agents of public food procurement, school feeding programs are now promoted as potential solutions to lowering the environmental footprint of food and generating agricultural and food systems transformation.[8–12]

It is true that, at the scales represented globally – roughly 10% of children around the world benefit from government-provided school meals[13,14] – school feeding programs are important food purchasers. Program decisions about what to serve and any quality specifications they adopt (for example, requiring organic or local food) shape food demand, which in turn alters the landscape of incentives faced by producers. Much emphasis has thus recently been placed on the potential for school feeding programs to meet triple objectives of food and nutrition security, climate mitigation in agriculture, and enhanced educational outcomes at school.[15,16] However, school meals are linked to climate in both directions. In addition to generating climate and environmental impacts via food production, processing, transportation, and waste, school feeding programs are also highly exposed to climate, as conditions can alter food availability and prices. In fact, the same features that make school feeding programs powerful agents of food system transformation – that they are large and centralized procurement agents – also leave them potentially vulnerable to climate (and climate-related) disruptions to local and global food systems. It is especially important to consider these risks given that the beneficiaries of school feeding programs are definitionally vulnerable children who typically lack economic agency and can suffer long-run consequences from even short-run disruptions in their access to food.

In this report, we provide the first estimates of the climate risk faced by school meal programs, and analyze several potential pathways towards climate resilience for both individual programs and across the school meals social safety net as a whole. We believe this report will serve the school meals community in at least four ways: first, the analyses outlined here can be applied to any individual program to understand the current pressures of climate change on the local "school plate"; second, these analyses also provide an opportunity for programs to explore "hardening" their current practices against likely climate-driven disruptions through sourcing decisions. Third, international actors working across school feeding programs (and often across countries) may be interested in the potential climate-driven impacts to school meals at regional and global scales, or correlated impacts across countries, along with opportunities for regional or networked resilience. Finally, we hope that the analysis provided here can help motivate much-needed work on the types of local, year-round, nutritious and climate-hardy production systems that can support school meal programs, and the design of new procurement policies to link those resilient agricultural systems to schools.

This report begins with an overview of the data sources used, followed by a detailed explanation of methodology. The Results section presents our team's main empirical findings on the current 'silent' cost of climate change to school meals, and opportunities for resilience through adoption of regenerative agricultural practices and climate-smart procurement policies. We then provide some detailed examples drawn from case studies and highlight important "climate pressure points" in the school feeding landscape that have emerged from this research. Our discussion concludes with a roadmap for next steps towards a world of resilient school meals for all.

Data Sources

School Meals Data

The primary data source for school feeding program information is the Global Survey of School Meal Programmes, conducted by the Child Nutrition Foundation (GCNF).[14] This survey was conducted from November 2023 to July 2024, and focused on school feeding programs for the school year beginning in 2022 (these data are described in detail in the accompanying GNCF materials and website[17]). We use the harmonized program-level data (meaning we treat programs in the same country independently), and use information about the number and fraction of eligible school children served, the types of procurement policies used (i.e., whether food is procured domestically or internationally, and whether any is provided as aid), and the embedded food frequency questionnaire, in which program staff answer questions about the types of food served in typical school meals and the frequencies at which they are served (i.e., daily, 2-4 times per week, weekly, monthly, or rarely). Several programs only partially responded to the survey (for example, they included overall program coverage information but did not submit food frequency responses), so not all countries shown in Figure 1 are included in the full set of analyses contained in this report.

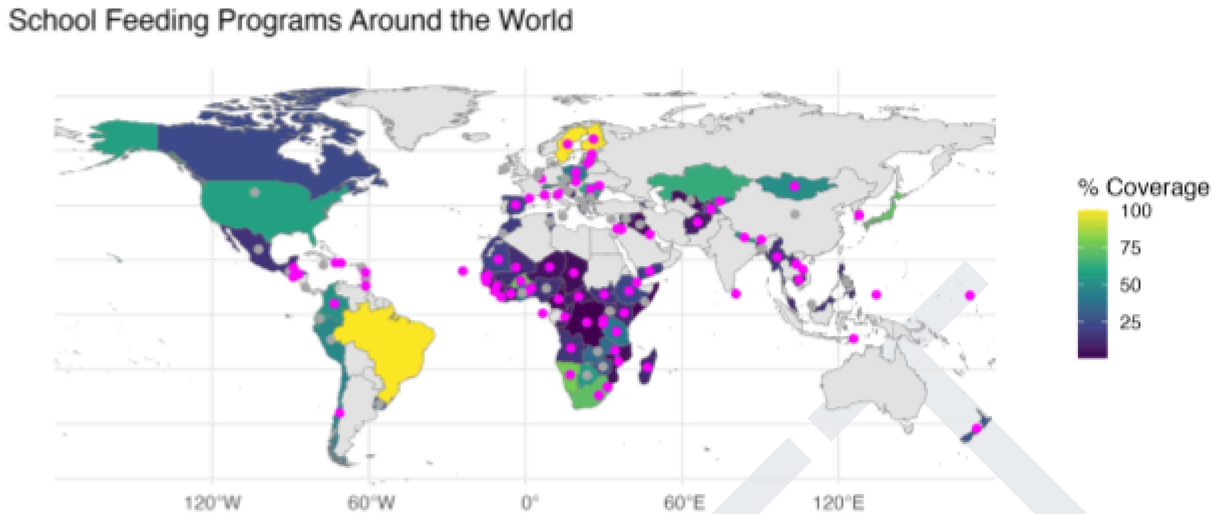


Figure 1. Overview of school feeding programs and their characteristics, from national school feeding programs that responded to the Global Survey of School Meal Programs in 2022-2023. Fill color indicates the percentage of children (preschool-secondary) who are enrolled and receiving meals through school programs (where brighter is a higher percentage). Dots in each country indicate whether program food products are procured internationally (magenta = yes/international; grey = no/domestic). Countries with no dot (e.g., Brazil) did not report procurement practices; countries with no fill (e.g., China) did not report coverage numbers.

Climate and Crop Data

To estimate climate impacts on crop yields, we assemble a dataset combining crop yield data and weather data for all countries and crops we consider in our study. We get crop yield data for each country for each crop from the United Nations Food and Agriculture Organization (FAO) statistical database (FAOSTAT)[18] from 1961-2023. For weather data, we calculate mean temperature and total precipitation for each crop and country combination over the area in which that crop is grown in that country. To get crop footprints, we leverage the CROPGRIDS dataset[19], which contains georeferenced rasters on harvested area at 0.05x0.05 degree resolution for 173 crops; we include all crops for which harvested area is greater than zero. We then retrieve georeferenced temperature data from the global ERA5 reanalysis product[20] and precipitation data from CHIRPS[21], and compute monthly mean temperatures and total precipitation for each year, averaged over the crop footprints from each country. We construct this dataset pairing weather data with crop yield data for all years crop and country combinations, creating a panel dataset that allows us to identify the causal effect of changes in temperature and precipitation on crop yield.

Maps for a subset of the crops analyzed are shown in Figure 2, with crop area averaged national temperature and precipitation averages shown in Figure 3.

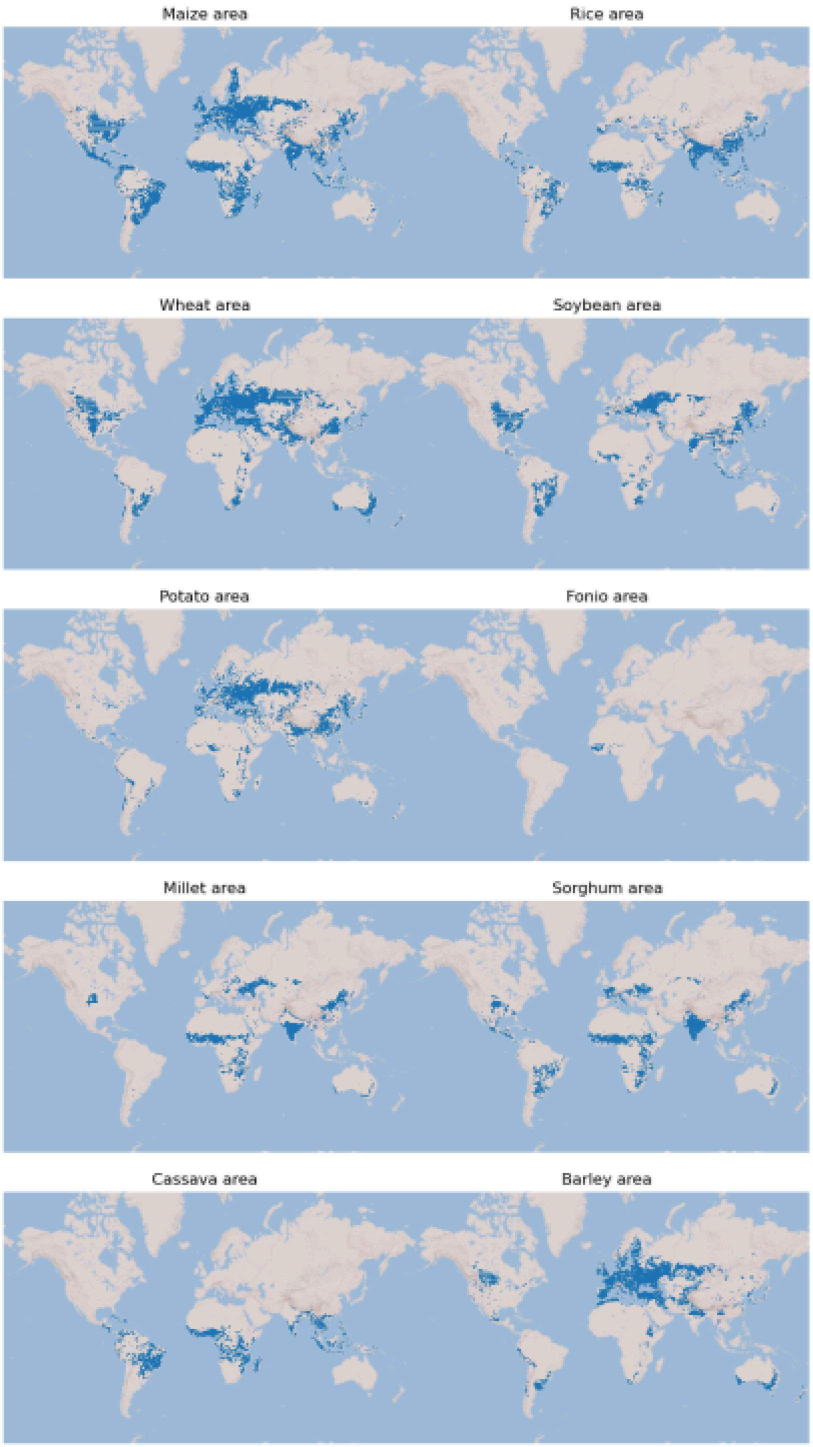


Figure 2. The growing areas for a subset of crops analyzed in this study. We source growing areas for all crops from the CROPGRIDS dataset, and we use these areas to compute mean temperature and total precipitation combined with weather data from ERA5 and CHIRPS to measure crop-specific exposure to climate. Some of these crops are primarily grown in the global south, such as cassava, millet, fonio, and sorghum.

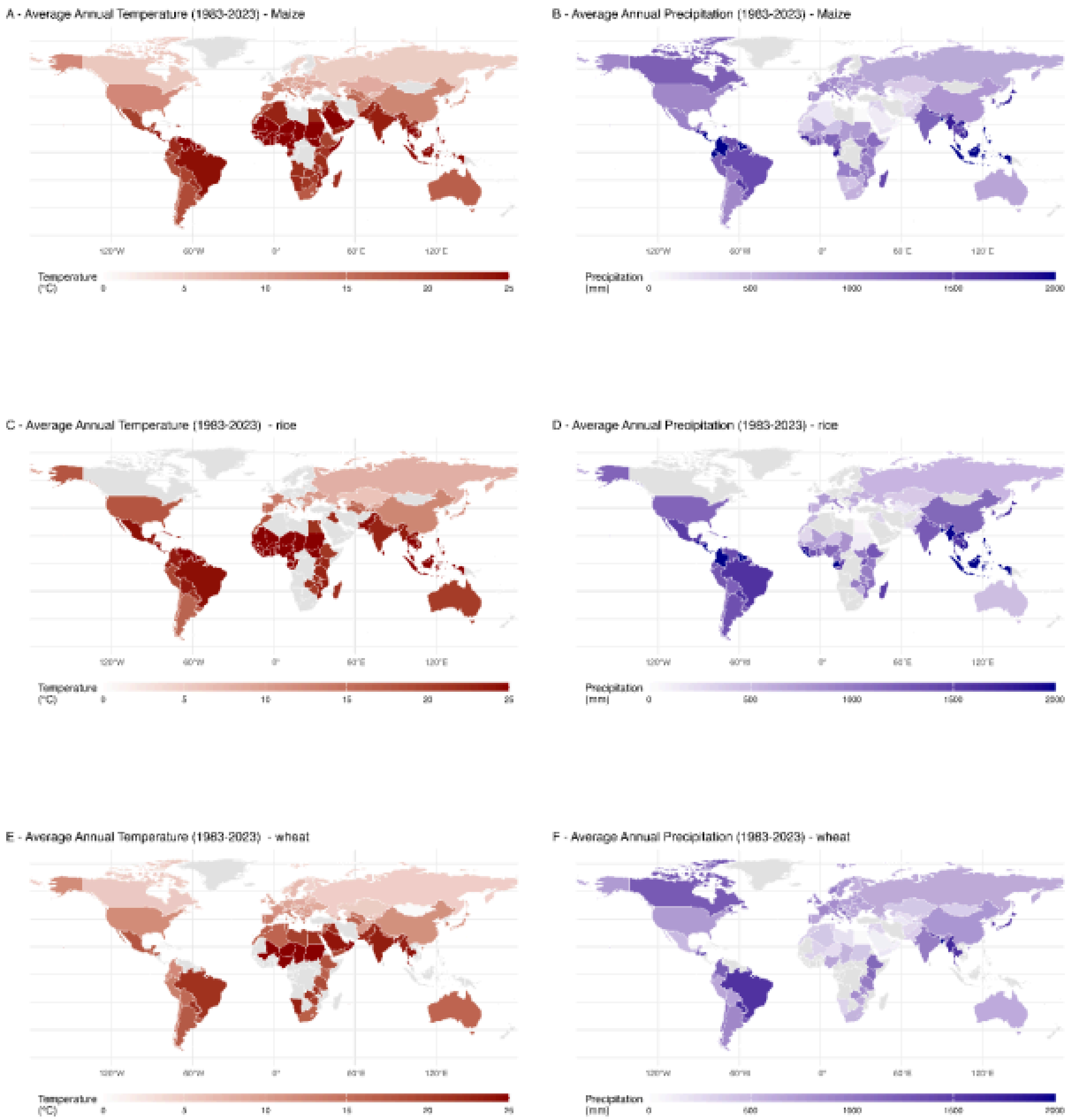


Figure 3. Spatial distribution of average annual temperature and precipitation for major staple crop production areas, 1983-2023. Maps show country-level averages for maize, rice, and wheat around the world.

Price Data

We also draw price information from the FAOSTAT database. FAOSTAT reports official national level data received from FAO Members on prices their farmers obtain. We focus on producer prices (also referred to as farm-gate prices), or the prices received by the farmer for primary crops as collected at the point of sale. These data therefore do not include costs that might accrue beyond the farm gate, such as transportation costs, warehousing costs, processing costs or other charges for selling the produce. The FAO price data contains PPI-adjusted price data reported by member countries from 1991 to 2024 for 161 countries for a wide range of crops; we use this data in combination with our yield and weather data to explore the relationship between weather, production, and crop prices.

Regenerative Agriculture Data

A wide variety of agricultural studies have compared different outcomes (e.g., yield, soil carbon, biodiversity, profits) between crops grown under “business-as-usual” conditions and crops grown under one or more management techniques meant to enhance soil health.[22–25] Here, we focus on the impacts of these regenerative practices (that is, farmers using one or more of: reduced tillage, cover cropping, diversified crop rotations, crop residue retention) on crop yields (amount produced per hectare). We focus on the four most widely-grown crops in the world (maize, rice, soybean, and wheat) and leverage the larger amount of data for those staples to most effectively extrapolate potential regenerative agriculture impacts worldwide. Winter and spring wheat were considered jointly for impacts.

We use regenerative potential estimates that were produced by report contributors Adam Pellegrini and Dave Encarnation from Stanford University and Cambridge.[26] The underlying data for these projections come from ~490 papers and ~3000 paired yield observations around the world (Figure 4). Paired observations compare the use of regenerative practice(s) with a conventional control, keeping other farm management practices the same. Data were matched to 8 climate classifications based on thermal (boreal, temperate, subtropical, tropical) and moisture (dry, moist) regimes, which allowed us to extrapolate impacts to regions that did not have regenerative agriculture trials themselves. National-level “regenerative transformation potentials” were generated by area-weighted averages of yield change for each crop across different climate classifications in each country, where weights reflect the proportion of each crop’s growing area in each climate category in each country. Yield change estimates were calculated for four crops (rice, maize, soybean, wheat), and the regenerative potential of spring and winter wheat were estimated separately based on underlying crop growing area maps. As seen in Figure 4, the mean net impacts across major crops is almost always expected to be positive, and sometimes quite large. Standard errors are not shown in the figure, but it is worth noting that the lower confidence bound for almost all countries includes zero, reflective of both the vast differences in implementation (e.g., reduced tillage could look quite different across two studies, but both be categorized as regenerative) and the different aims of the underlying studies (e.g., focused on different outcomes). We do not incorporate any cost estimates of a regenerative agricultural transition, but simply report technical potential.

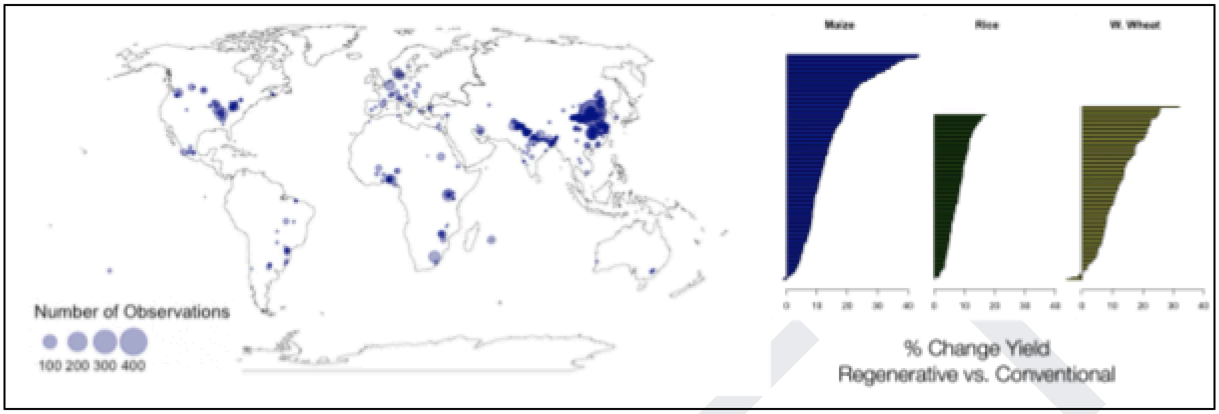


Figure 4. Regenerative agriculture data used in this study. (left) The underlying field trial data were gathered from ~490 studies and comprised ~3000 paired observations that compared the addition of one or more regenerative practice(s) to the absence of that practice (the conventional control). Yield differences from these paired observations were then mapped globally by climatic classification within and across countries, and bootstrapped to develop uncertainty metrics. Here we present and use mean values. (right) The mean country-level anticipated changes in yield for a transformation to regenerative agricultural systems for maize, rice, and winter wheat (as a few examples) are almost all anticipated to be positive, with a few countries where the mean is slightly negative (country names not shown, but are presented in descending order of anticipated impacts; the order is different across crops). Data were provided by Adam Pellegrini and Dave Encarnation.

We additionally gathered existing data on less widespread (or less studied) crops.[27–29] We have examined these data but they typically did not have enough coverage for any individual crop to justify global extrapolation. In the absence of that capacity, we wanted to avoid any scenario whereby we had projections for regenerative potential for the same crop in some countries but not others, as this would create comparisons that could not be straightforwardly interpreted.

Case Studies

In addition to the GNCF survey data, we conducted detailed literature-based case studies for 7 programs, and spoke with key leaders from 4 programs in 1-2h interviews. The literature “deep dives” (for Kenya, Ethiopia, Burkina Faso, Ghana, Philippines, Brazil, and the United States) helped us to understand the programs in greater detail, and in particular many of the findings (and caveats) present in scientific evaluations of these programs. Interviews (with staff from Kenya Food for Education Program, Ethiopia Home Grown School Feeding Program, Philippines School Based Feeding Program, Brazil National School Feeding Program) were especially valuable for understanding the constraints (around procurement but also more broadly) faced by programs, their latitude in decisionmaking, and how they think about (and implement strategies for) balancing nutrition, climate resilience, and cost.

Methods

Climate variability and climate change could impact school feeding programs via multiple channels. For example, in terms of operations, extremely hot conditions could negatively impact program staff or flood conditions could make logistics difficult or even impossible. The existing harmonized data from GNCF do not provide enough detail to reliably estimate potential present climate risk to program operations; here we instead focus on climate impacts on the agricultural products that comprise school meals in all programs.

It is well documented that anthropogenic climate change has largely had negative impacts on agricultural productivity, across most regions and agricultural products.[30] However, the evidence base is strongest for a few staple crops (rice, wheat, maize, soybeans, cassava, and sorghum)[31] that are very important for overall caloric sufficiency and protein globally, but only cover part of what is served around the globe in school meals. As we describe below, we developed climate impacts relationships for rice, wheat, maize, and soybean globally, and for a broader suite of crops for sub-Saharan Africa where damages are expected to be highest, but also the basket of foods comprising school meals is very diverse.

For each school feeding program reporting to the GNCF survey we sought to understand and quantify two phenomena: (a) the 'silent' cost of climate change and (b) the resilience opportunity of regenerative agriculture. We additionally aimed to characterize (c) the role that climate-smart international procurement (trade) might play in promoting resilience. We describe these methods in detail below, but briefly: we linked information on the composition of school meals for each program to climate-productivity relationships that we derived from historical agriculture and climate data, along with regenerative agriculture and international and domestic price data for major crops around the world. We then compared price volatility domestically to international price volatility to understand the conditions under which trade might lead to either vulnerability (via trade-linked climate shocks to imported foods) or resilience (by providing a mechanism to smooth local volatility).

These methods are shown in schematic overview format in Figure 5, and described in detail below.

A: Silent Cost of Climate Change

B: Regenerative Agricultural Potential

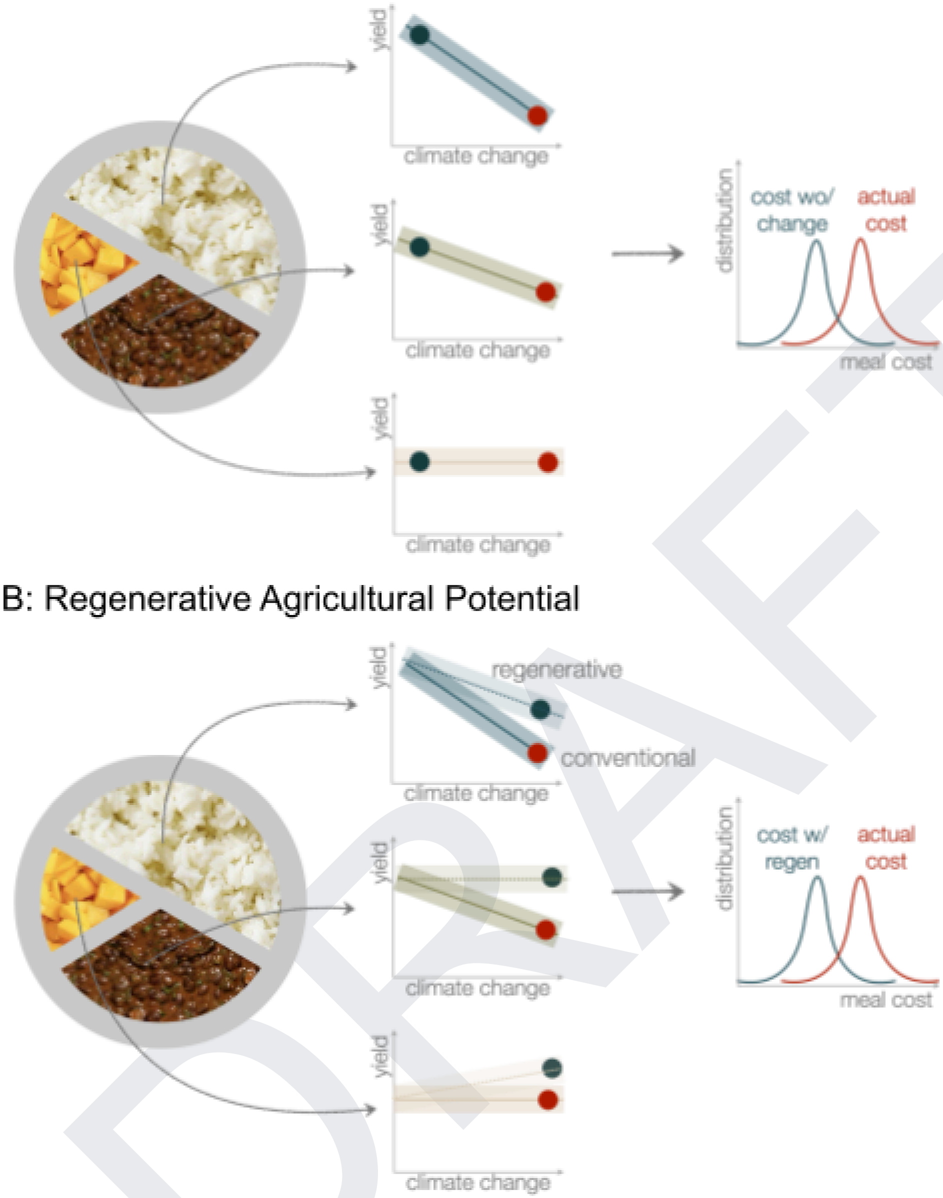


Figure 5. Cartoon schematic of the methods used to calculate (A) the Silent Cost of Climate Change on school feeding programs; and (B) the Regenerative Agricultural Potential for school feeding programs.

Plate Composition

We merge data from the FAO Supply Utilization Accounts (SUA) on total food supply in 2022, FAO Yield data, and the Global School Meals reported food group frequencies to estimate the average composition of school meal plates. Representative plates are created by multiplying the food group composition based on food group frequencies with the respective country food basket from FAO data, as described below.

First, we harmonize food products and food groups across the three datasets. We match the FAO SUA food products to a shorter list of FAO Yield food products. FAO Yield products are then categorized within each of the food categories included in the School Meals dataset. Foods are categorized according to FAO guidance on assigning individual foods to food groups as used in common dietary diversity indices.[32,33] Some food products are included in multiple food groups (e.g., maize is assigned to whole grains, blended grain-based products, and refined/milled grains), while others are not categorized within a food group if they have low nutritional value (e.g., herbs or spices) or are non-specific (e.g., mixed grain). Animal-source food groups are excluded, with the exception of eggs, as we do not estimate yield impacts for animal products in our analyses. Using the harmonized datasets, we create country-specific food baskets, with proportional estimates of the FAO Yield food products categorized within each food group.

Figure 6. School meal plate composition globally, averaged across 182 programs in 118 countries. The inner ring shows the food groups reported to the GNCF global survey on school meals, and the outer ring shows how such product groups are matched with national supply and utilization accounts to estimate the specific food groups likely represented on the plate.

Second, school meal data on the frequency of food group consumption is used to estimate the average proportional plate for each country. Frequencies are assigned based on standard frequencies from Food Frequency Questionnaires[34] (1 for daily, 0.43 for 2-4 times per week, 0.14 for weekly, 0.08 for monthly, and 0 for rarely). These frequencies are then used to estimate the proportion of each food group on the school meal plate relative to the total frequency of food groups. Only grain, fruit, vegetable, and oil food groups are modeled on the plate, to be used in conjunction with the yield estimates. Thus, several food groups included in the School Meals dataset are not included in the plate estimates. Excluded food groups include salt, sweets and ice cream, dairy, deep-fried foods, eggs, semi-solid and solid fats, fish and shellfish, poultry and game meat, processed meat, red meat, and other.

These data are shown in aggregate globally in Figure 6; Appendix C contains more detailed information on food frequencies, and specific examples of matching survey data to SUA information for four individual case study programs.

Climate Impacts

Climate impacts on crop yields: We estimate the effects of climate change on crop yields at the global scale using historical data on crop productivity and weather conditions and exposure of that crop. We follow closely the methodology of Lobell et al. (2011)[35], which estimates "impact functions" that capture the statistical relationships between temperature, precipitation, and crop yields. These statistical relationships are often called “damage functions” because they can be used to express, for example, the expected changes in crop yields for (e.g.) a 1°C local increase in temperatures above average or a 100mm local deficit in rainfall (which are often negative, hence “damage").

Our analysis uses annual country-level yield data from FAOSTAT for the 1983-2023 period, combined with gridded annual temperature data from ERA5 reanalysis and precipitation data from CHIRPS aggregated to the country level. We estimate separate damage functions for four major staple crops (maize, rice, wheat, and soybean), using panel regression models with country fixed effects to account for time-invariant country-specific differences in production systems, such as soil quality, infrastructure, and baseline crop management practices. The models include temperature (T), precipitation (P), and their quadratic terms (T^2, P^2) to capture nonlinear crop responses to weather, and control for technological progress through country-specific linear and quadratic time trends, allowing us to isolate the contribution of climate trends to observed yield changes. To account for differences in growing practices and conditions between countries that affect climate sensitivity, we group countries with similar agricultural attributes before estimating yield responses to weather variables. Countries are stratified into four quartiles based on average crop yields (1983-2023), with separate damage functions estimated for each quartile-crop combination following Lobell et al. (2011). This stratification allows climate sensitivities to vary across production systems with different management intensities, as higher-yielding systems (with greater fertilizer and irrigation use) may exhibit different weather responses than lower-yielding systems. As a robustness check, we also estimate a global pooled model with no country grouping (see Appendix A).

The primary objective is to construct counterfactual scenarios comparing observed yields to what they would have been in the absence of climate trends. This approach allows us to quantify how much historical changes in temperature and precipitation across different regions have contributed to—or constrained—crop productivity gains over the past four decades. Detailed model specifications and estimation results are provided in the Appendix A.

For each country, we detrend the temperature and precipitation time series by removing their linear trends and restoring 1983 baseline values. Using our estimated damage functions, we then predict yields under multiple scenarios of historical T and P: (i) historical climate as observed, (ii) with temperature trends removed, (iii) with precipitation trends removed, and (iv) with both trends removed. The net climate impact equals the divergence between scenarios (i) and (iv) over time, while scenarios (ii) and (iii) allow us to attribute impacts separately to temperature versus precipitation trends.

This section makes two key contributions to the literature on climate impacts on agriculture. First, we update and extend the damage function estimates of Lobell et al. (2011) to the 1983-2023 period, incorporating an additional 15 years of climate and yield data. Second, we expand the analysis beyond the four major staple crops to include additional food groups critical for food security and nutrition. While our global-scale analysis focuses on staple crops -maize, rice, wheat, and soybean- we present damage function estimates for Africa across a broader set of crop categories, including other grains (e.g., millet, sorghum, oats), other pulses (e.g., lentils, chickpeas, beans), roots and tubers (e.g., cassava, yam, potato), and vegetables. This expanded crop coverage allows us to more comprehensively assess the "hidden costs" of climate change for African agriculture, particularly for crops that, while locally important, receive less attention in global assessments. Future work will extend these damage functions for non-staple crops to the global scale and refine the climate variables by using growing-season-specific temperature and precipitation rather than annual averages.

Climate impacts on food prices: Our analysis investigates how climate-induced yield variations translate into producer price responses. We begin by estimating the relationship between crop yields and weather fluctuations, and then examine how these yield shocks affect agricultural prices.

We use annual producer price data from the FAOSTAT database, expressed in local currency and normalized using the Producer Price Index (PPI, 2014–2016 = 100). The analysis focuses on four major staple crops - maize, rice, wheat, and soybeans -and illustrates results for countries in Africa, though the empirical approach has been implemented more broadly across crops and regions. To address outliers and ensure robustness, producer prices are trimmed at the 99th percentile.

Our main specification estimates the elasticity of producer prices with respect to crop yields. We run the following regression separately for each crop and in a pooled sample including crop fixed effects:

$$ln(P_{ct}) = \alpha + \beta\, ln(Y_{ct}) + \mu_c + \tau_t + \varepsilon_{ct}$$

where $\ln(P_{ct})$ denotes the logarithm of the producer price in country c and year t, $\ln(Y_{ct})$ is the logarithm of yield, μ_c are country fixed effects, and τ_t are year fixed effects.

We estimate two versions of this model:

1. Observed yield specification - uses realized yield data to estimate the empirical relationship between yields and prices. This captures how actual production changes are associated with price movements.
2. Predicted yield specification - replaces observed yields with model-predicted yields based solely on weather variables (temperature and precipitation) and their trends. This allows us to isolate the impact of climate-induced yield shocks on prices, holding other determinants of yield constant.

The estimated coefficient β represents the price–yield elasticity - the percentage change in producer prices associated with a one-percent change in yields. A negative coefficient indicates that higher yields, reflecting greater supply, tend to reduce prices, consistent with standard supply–demand mechanisms. Conversely, a positive coefficient would suggest that yield shocks coincide with price increases, potentially reflecting broader market frictions, storage constraints, or general equilibrium effects. Comparing results across the two specifications helps identify how much of the observed price variability is directly attributable to weather-induced productivity shocks versus other factors affecting both yields and prices.

Finally, while standard errors are clustered at the country level, additional adjustments may be needed in future work to account for the fact that predicted yields are estimated regressors, which could affect inference.

Climate Vulnerability

The climate impacts functions described above allow us to estimate how much food *would have* been produced in present times *had climate change to date not occurred*, and to compare those estimates to observed agricultural production. For each country-crop pair, we therefore have an estimate of how much climate change to date either hurt or helped production (most estimates are negative, but not all, as shown in Figure 7).

We connect these product-specific changes in productivity (yield) to the foods that comprise each school program's "typical plate" to obtain a climate impact estimate on the change in the number of meals that the program as a whole could have served in a no-climate change world. This is described qualitatively in Figure 5A and quantitatively by the equation:

$$\Delta N_{(climate)\ p,c} = N_{p,c} \times (1 + \sum_{k} (Q_{k,p,c} \cdot \Delta Y_{k,c})$$

Here ΔN is the estimated change in the number of meals due to climate change in country *c* and program *p*. We multiply the fraction of each product *k* in the menu of program p by its local climate change impacts on crop yields, ΔY. We sum this quantity over all products in the school menu. We then assume that the program's overall budget does not change, and make additional simplifying assumptions about the economic contexts surrounding school feeding programs because we cannot predict international prices or other disturbances that might affect local food availability or procurement costs. Instead, we straightforwardly assume that increased yields translate linearly to a reduction in prices, and the ability to feed more students per dollar (or conversely that negative yield impacts mean reduced product availability and higher prices). Put another way, any reduced or increased food availability (and thus cost) is translated directly into an increase or decrease in the number of students served with daily meals by the program.

For this analysis, we additionally assume that all production is domestic; ΔN thus represents the change in the availability of meals if every product were domestically produced. The Global Survey of School Feeding Programs contains some information on domestic versus international procurement, but we are not able to link *specific individual* imported foods to their production locations except when we have been able to communicate directly with program staff (case studies). So we start from the perspective of locally grown meals, which is a stated priority of many of the surveyed programs. We also do not include meat or dairy in our climate change impacts analysis because reliable production data are very difficult to obtain across a wide swath of countries. In most programs these are minority components, although very important nutritionally (and they often depend on climate conditions for feed, etc.).

A final caveat is that in most cases we do not know the exact amounts of specific products served in each meal program - we only know food categories and must infer from domestic supply accounts what products are likely to be served based on what is typically available in that country.

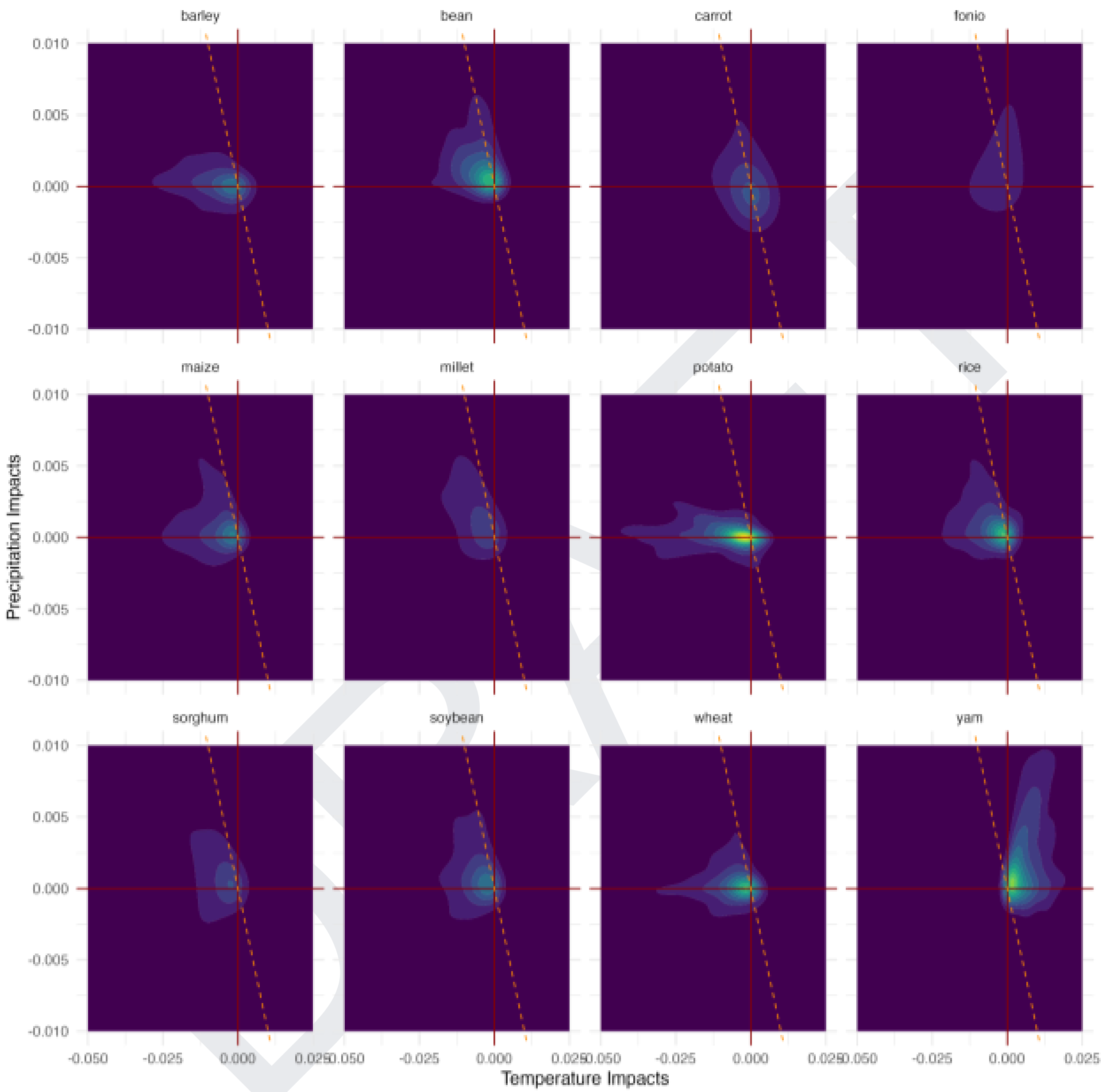


Figure 7. Global distribution of temperature and precipitation impacts on crop yields over time for a subset of 12 major crops considered in this study.

Resilience and Regenerative Agriculture

We define the opportunity of a domestic shift to regenerative agricultural production in a similar manner to climate impacts; here, however, we quantify the change in the number of children who could be served if domestic cropping systems were to transition to regenerative production (see section on Regenerative Agriculture Data for more information on how we produce country-specific estimates of this technical potential). This is described qualitatively in Figure 5B and quantitatively by the equation:

$$\Delta N_{(regen)\ p,c} = N_{p,c} \times (1 + \sum_{k} (Q_{k,p,c} \cdot \Delta R_{k,c})$$

Here ΔN is the estimated change in the number of meals due to a switch to regenerative agriculture in country *c* and program *p*. We multiply the fraction of each product *k* in the menu of program p by its local predicted change in yields from adopting regenerative agricultural practices, ΔY. We sum this quantity over all of the major grains in the school menu. As above, we assume that increased yields translate linearly to a reduction in prices, and the ability to feed more students daily on the same program budget.

Role for Climate-Smart Trade

In addition to analyzing the direct effects of climate-induced yield variations on prices, this report examines the role of trade in shaping food price dynamics and mitigating the impacts of adverse production shocks. Trade can influence domestic food prices through two main channels. First, by allowing countries to import food when domestic production is low, trade can reduce price volatility and serve as a form of insurance against local shocks. Second, trade can transmit production shocks across borders, exposing countries to external supply fluctuations through international markets.

To investigate these mechanisms, we conduct three complementary analyses:

Comparing international and domestic price variability: We first explore how international prices vary relative to domestic producer prices. Using international price data from FAOSTAT and local producer price indices (PPI, base 2014–2016 = 100), we compare the volatility of international and domestic prices for the main staple crops (maize, rice, wheat, and soybeans). We focus on years 2000-2023 to match the timeframe available for international prices for these crops. This comparison provides insight into whether international markets can serve as a stabilizing force for domestic prices. This analysis also motivates ongoing work on the potential benefits of international trade as a mechanism for risk pooling - where countries facing opposite or uncorrelated shocks could reduce aggregate volatility through trade. We explore the volatility of international and domestic prices by computing the coefficient of variation for each country and crop: standard deviation of prices within country and crop, normalized by mean prices within country and crop. The coefficient of variation is calculated as follows for crop i in country c and year t:

$$CV_{dom,ic} = \frac{\sigma(P_{dom,ict})}{\bar{P}_{dom,ict}} ; CV_{int,i} = \frac{\sigma(P_{int,ict})}{\bar{P}_{int,ict}}$$

Self-reliance and heterogeneity in price responses: Next, we test whether the responsiveness of prices to yield shocks depends on a country's degree of trade integration. Using FAOSTAT Food Balance Sheets data, we construct a *self-reliance ratio* for each country and crop, defined as the average production divided by average domestic supply over the study period. This measure captures how dependent a country is on domestic production relative to imports. We then estimate heterogeneous effects of yield shocks on prices by interacting yield changes with the self-reliance ratio. This allows us to test whether countries that are more open to trade experience smaller price increases when domestic yields fall. The self reliance ratio is calculated as follows for country c and crop i:

$$SR_{ic} = \frac{\overline{Production}_{ic}}{\overline{Domestic\ Supply}_{ic}}$$

We use this variable to explore whether the effect of yields on prices varies by how self-sufficient a country is in its production.

Event study of trade adjustments following production shocks: Finally, we assess how trade flows respond to production shocks using an event study framework. For each country and crop, we identify the year with the lowest yield ("bad year") and trace how imports and exports evolve in the years following the shock (one, two, and three years after). The specification includes country, year, and crop fixed effects to control for time-invariant and common shocks. We perform this analysis for the four main staple crops and focus on African countries for comparability with the price–yield analysis. This exercise provides evidence on whether trade flows adjust in response to domestic production shortfalls—either mitigating or amplifying their effects on local markets.

We use the following model, where TradeFlow is imports or exports of crop i in country c at time t + k, and D is an indicator equal to 1 if year t+k is k years relative to the shock.

$$TradeFlow_{ict+k} = \alpha + \sum_{k=-10, k\neq 0}^{10} \beta_k D_{ic,t+k} + \mu_i + \lambda_t + \delta_c + \varepsilon_{ict}$$

Together, these analyses shed light on how trade can act as both a buffer and a transmission channel for agricultural shocks, and how countries' integration into global food markets shapes their exposure and resilience to climate-induced yield variability.

Results

School Meal Program Summary

This analysis covers 210 school feeding programs in 127 countries that responded to the GCNF's survey (out of 194 contacted; see ppendix C for a supplementary table showing participant countries). These programs served a reported 231.5 million children in the 2022-2023 school year, although a handful of countries (perhaps most notably, China) do not report student numbers, so this is almost certainly an underestimate of the total number of children served through national school meal programs. Nevertheless, this number is about 10% of children under the age of 18 globally. As shown in Figure 8, these programs vary in size by orders of magnitude, from a few thousand to tens of millions of children served daily.

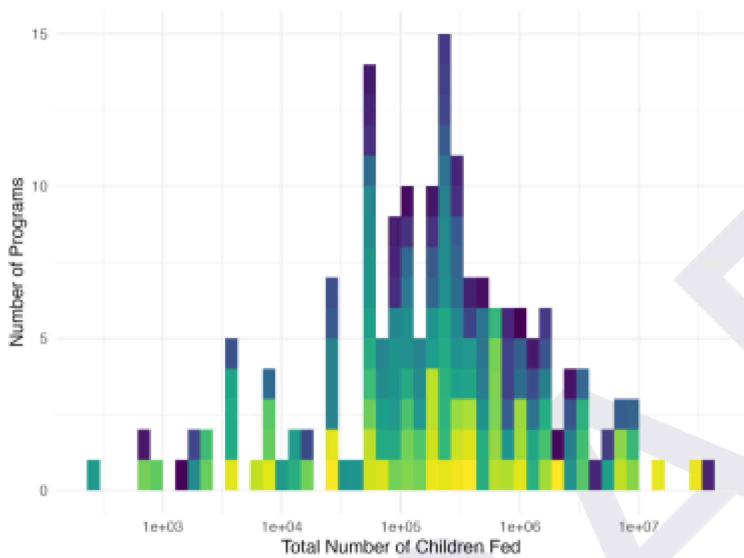


Figure 8. Distribution of size of school feeding programs reporting to the GNCF Global Survey of School Feeding Programs for the 2022-2023 school year. (Each country's programs are shown in a different color to help visualize the number of programs in each size bin.)

These data are summarized in detail in various GNCF reports, but we also want to highlight several key features of school feeding programs relevant to agricultural systems transformation and climate resilience. First, the budgetary structures of programs vary widely, with 91 reporting programs having a dedicated line item in the national budget (34 do not); the amount of the budget spent on food varies widely, from 0 to 100%, with a median of 80% (mean of 75%) across reporting programs. The calculated cost per child per year also ranges from 0 (for programs based on aid) to $1200 USD and is highly skewed (median of $57 and mean of $154). Half of reporting programs are thus spending less than $0.30 per child per day (based on 180 days), and this may be for more than one meal (e.g., a warm lunch and take-home rations).

Most programs are purchasing most food domestically (median 90%, mean 69%), but a handful of programs are exclusively or almost exclusively purchasing all food internationally. Conversely, in-kind food donations are largely international, reflecting the continuing importance of aid (in 2022-2023) for school feeding programs.

Plate Summaries

A total of 182 programs in 118 countries provided information on the food group composition of school meals. Countries' school feeding programs served, on average, 7.1 of 14 food groups[1] at least monthly, ranging from 1 to 14 (Figure 9). In Sub-Saharan Africa, countries served an average of 5.5 (± 2.3) food groups. Across all food categories reported in the survey, around 70% of all programs globally provided salt, legumes, and liquid oils (Table 1). Whole grains were provided by 63% of programs, refined/milled grains by 54%, and blended grain-based products by 31%. Whole grains and refined/milled grains were predominantly provided daily or 2-4 times per week (Appendix C Figure 1). Half of the programs served dairy, fruits, vegetables, and fish/shellfish, and 62% served dark leafy greens. Dark leafy greens and other vegetables were typically provided several times per week or weekly, though in East

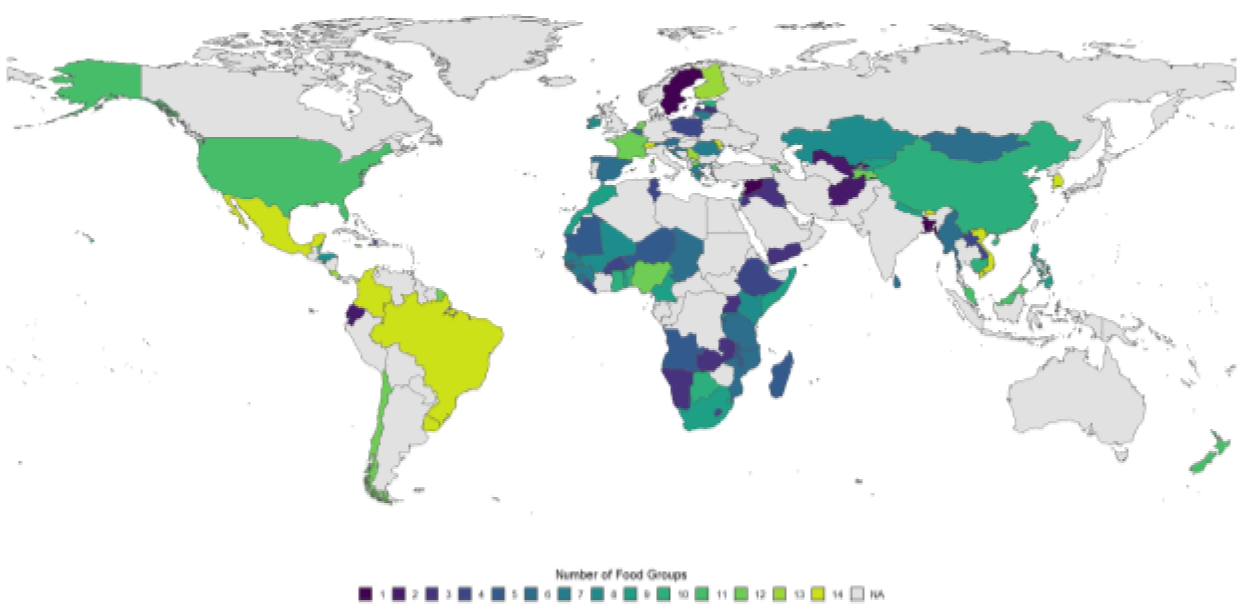


Figure 9. Number of food groups served, at least monthly, by country. A weighted average by number of children fed is shown for countries with multiple school feeding programs. Food group categories include: grains/cereals, cruciferous vegetables, dark green leafy vegetables, deep orange vegetables and tubers, fruits, legumes, fats, nuts and seeds, other vegetables, dairy, eggs, fish and shellfish, meat, white roots and tubers.

[1] Food groups included the following categories reported in the survey: grains/cereals (blended grains, refined grains, or whole grains), cruciferous vegetables, dark green leafy vegetables, deep orange vegetables and tubers, fruits, legumes, fats (liquid oils or semi-solid and solid fats), nuts and seeds, other vegetables, dairy, eggs, fish and shellfish, meat (poultry and game meat, processed meat, or red meat), white roots and tubers. We exclude deep-fried foods, sweets and ice cream, salt, and other from this count.

Asia leafy greens were served daily by more than half of programs. Dairy was the most common animal-source food, provided daily by one-third of programs, and 2-4 times per week or weekly by one-quarter of programs, respectively. Almost half of programs provided fish or shellfish, with many programs providing it several times per week in East Asia & the Pacific and Sub-Saharan Africa (Appendix C Figure 2). Red meat, poultry/game meat, or eggs were provided by about 40% of programs, typically weekly or several times per week. Provision of unhealthy food groups, including processed meat, deep-fried foods, and sweets and ice cream was less common and less frequent.

Our estimation of representative school meal plates, excluding animal-source foods and based on FAO supply utilization data, shows that wheat, rice, maize, and soya beans are the most common crops included in average school meals globally (Table 2). Grains, legumes, and liquid oils make up 56% of an average global “plate” (Figure 6). Regionally, wheat is the predominant cereal on plates for school feeding programs in Europe and Central Asia, North America, and the Middle East and North Africa; rice in South Asia and East Asia and the Pacific; wheat, rice, and maize in Latin America and the Caribbean; and maize and rice in Sub-Saharan Africa (Table 2). Soya beans are highly prevalent in the school meal plates of East Asia & Pacific, Latin America and the Caribbean, South Asia, and Sub-Saharan Africa. School feeding programs in

	Overall	East Asia & Pacific	Europe & Central Asia	Latin America & Caribbean	Middle East & North Africa	North America	South Asia	Sub-Saharan Africa
Number of countries	118	13	31	18	10	1	5	40
Number of programs	182	18	40	18	12	2	7	85
Salt	73.1	72.2	47.5	77.8	50.0	100.0	71.4	87.1
Legumes	72.5	55.6	60.0	94.4	33.3	50.0	71.4	83.5
Liquid oils	70.9	77.8	47.5	72.2	33.3	50.0	28.6	89.4
Whole grains	62.6	55.6	55.0	55.6	58.3	100.0	85.7	67.1
Dark green leafy vegetables	61.5	72.2	65.0	83.3	8.3	100.0	71.4	58.8
Other vegetables	55.5	72.2	80.0	83.3	41.7	50.0	42.9	37.6
Refined/milled grains	53.8	66.7	47.5	66.7	75.0	100.0	42.9	48.2
Fruits	53.3	66.7	90.0	83.3	75.0	100.0	57.1	22.4
Dairy	48.9	61.1	90.0	88.9	66.7	100.0	28.6	16.5
Fish and shellfish	46.7	66.7	47.5	83.3	41.7	0.0	28.6	37.6
Deep orange vegetables and tubers	42.3	55.6	55.0	77.8	41.7	50.0	14.3	28.2
Eggs	40.7	83.3	50.0	77.8	41.7	100.0	57.1	16.5
White roots and tubers	39.6	44.4	57.5	72.2	0.0	50.0	28.6	29.4
Red meat	38.5	77.8	52.5	61.1	25.0	50.0	28.6	21.2
Poultry and game meat	37.9	55.6	52.5	88.9	25.0	50.0	42.9	17.6
Cruciferous vegetables	32.4	38.9	60.0	72.2	8.3	50.0	14.3	14.1
Blended grain-based products	30.8	38.9	25.0	44.4	25.0	0.0	42.9	29.4
Nuts and seeds	26.4	55.6	30.0	33.3	25.0	50.0	28.6	16.5
Semi-solid and solid fats	23.6	33.3	40.0	50.0	25.0	0.0	42.9	7.1
Processed meat	19.8	33.3	40.0	33.3	16.7	50.0	14.3	4.7
Other	15.4	16.7	12.5	22.2	33.3	0.0	14.3	12.9
Deep-fried foods	13.2	22.2	20	22.2	25	0	28.6	3.5
Sweets and ice cream	7.7	16.7	12.5	5.6	8.3	0	0	4.7

Table 1. Proportion of school meal programs serving each food group (at least monthly). Values are %.

Sub-Saharan Africa have high diversity across different types of crops within food groups, including grains (maize, rice, wheat, sorghum, millet), oil crops (oil palm fruit, soya beans, coconut, sunflower seed, sesame seed), legumes (dry beans, soya beans, dry cow peas, dry peas, and others) and vegetables (lettuce and chicory, carrots and turnips, other fresh vegetables, onions and shallots, cabbages, tomatoes, pumpkins, squashes and gourds, and spinach), tubers, and nuts and seeds (Appendix C Figure 3). However, grains, legumes, and liquid oils are almost three-quarters of the average Sub-Saharan African plate, with almost 50% coming from just 5 crops: maize, rice, wheat, soya beans, and oil palm fruit.

Crop	Overall	East Asia & Pacific	Europe & Central Asia	Latin America & Caribbean	Middle East & North Africa	North America	South Asia	Sub-Saharan Africa
Number of countries	118	13	31	18	10	1	5	40
Number of programs	182	18	40	18	12	2	7	85
Wheat	10.0	4.8	12.7	10.9	32.8	36.9	13.5	5.5
Rice	9.7	15.7	1.1	8.5	6.4	5.2	27.9	11.7
Maize	7.3	0.9	1.7	6.5	2.6	4.4	4.4	12.3
Soya beans	6.7	5.8	1.3	11.7	3.8	2.7	8.3	8.7
Lettuce and chicory	5.6	5.7	5.7	7.6	1.2	6.8	5.7	5.7
Oil palm fruit	5.4	4.6	0.0	1.9	2.9	0.0	1.5	9.6
Beans, dry	4.1	0.9	1.1	3.5	0.3	0.3	0.5	7.3
Carrots and turnips	3.1	3.0	4.1	4.6	4.1	6.6	0.1	2.3
Sunflower seed	3.0	1.8	4.2	1.1	2.1	0.3	3.1	3.3
Coconuts, in shell	2.5	7.7	0.0	2.9	0.0	0.0	3.4	2.8
Other vegetables, fresh	2.2	4.2	1.2	2.4	0.3	0.1	6.0	2.2
Tomatoes	2.1	0.9	4.9	1.9	2.8	1.0	0.7	1.1
Onions and shallots, dry	2.1	2.6	3.3	1.7	2.8	0.3	0.9	1.4
Cabbages	1.9	1.6	3.3	3.2	0.6	1.2	1.4	1.2
Cow peas, dry	1.8	0.1	0.0	0.6	0.0	0.0	0.2	3.6
Bananas	1.7	1.4	3.6	1.8	2.7	3.2	0.6	0.8
Sesame seed	1.6	2.8	0.1	0.3	0.8	0.0	1.3	2.5
Potatoes	1.6	1.3	4.6	2.8	0.0	1.7	0.6	0.3
Other pulses	1.4	0.3	0.0	1.0	0.1	0.0	1.4	2.7
Pumpkins, squash and gourds	1.4	1.4	1.6	2.2	3.4	6.5	0.1	0.8
Peas, dry	1.1	0.2	1.5	0.4	1.5	0.1	0.5	1.2
Sorghum	1.1	0.1	0.0	0.1	0.2	0.2	0.0	2.3
Apples	1.0	0.7	2.9	0.7	1.8	3.0	0.2	0.1
Watermelons	1.0	0.4	2.8	0.7	2.8	1.5	0.1	0.1
Spinach	0.9	3.6	0.7	1.2	0.1	0.7	0.0	0.6

Table 2. School meal plate composition overall and by region, showing the 25 most common crops. Values are the proportion of each crop on the representative school meal plate, based on reported school feeding program food group frequency and FAO supply utilization account data. Averages are calculated across programs.

Climate Impact Functions

Descriptive Overview: We begin with some simple descriptive statistics of how global crop production and price environments have evolved over recent decades. Figure 10 shows temperature (left panels) and precipitation (right panels) trends during growing seasons for maize, rice, and wheat, 1983-2023. Trends are expressed as the total change over the 41-year period divided by the historical standard deviation

(1983-2023), providing a measure of trend magnitude relative to typical year-to-year variability. Values are calculated using linear regression of annual temperature and precipitation on year for each country. Red shading indicates warming or drying trends, blue indicates cooling or wetting trends, and white indicates near-zero trends. Grey

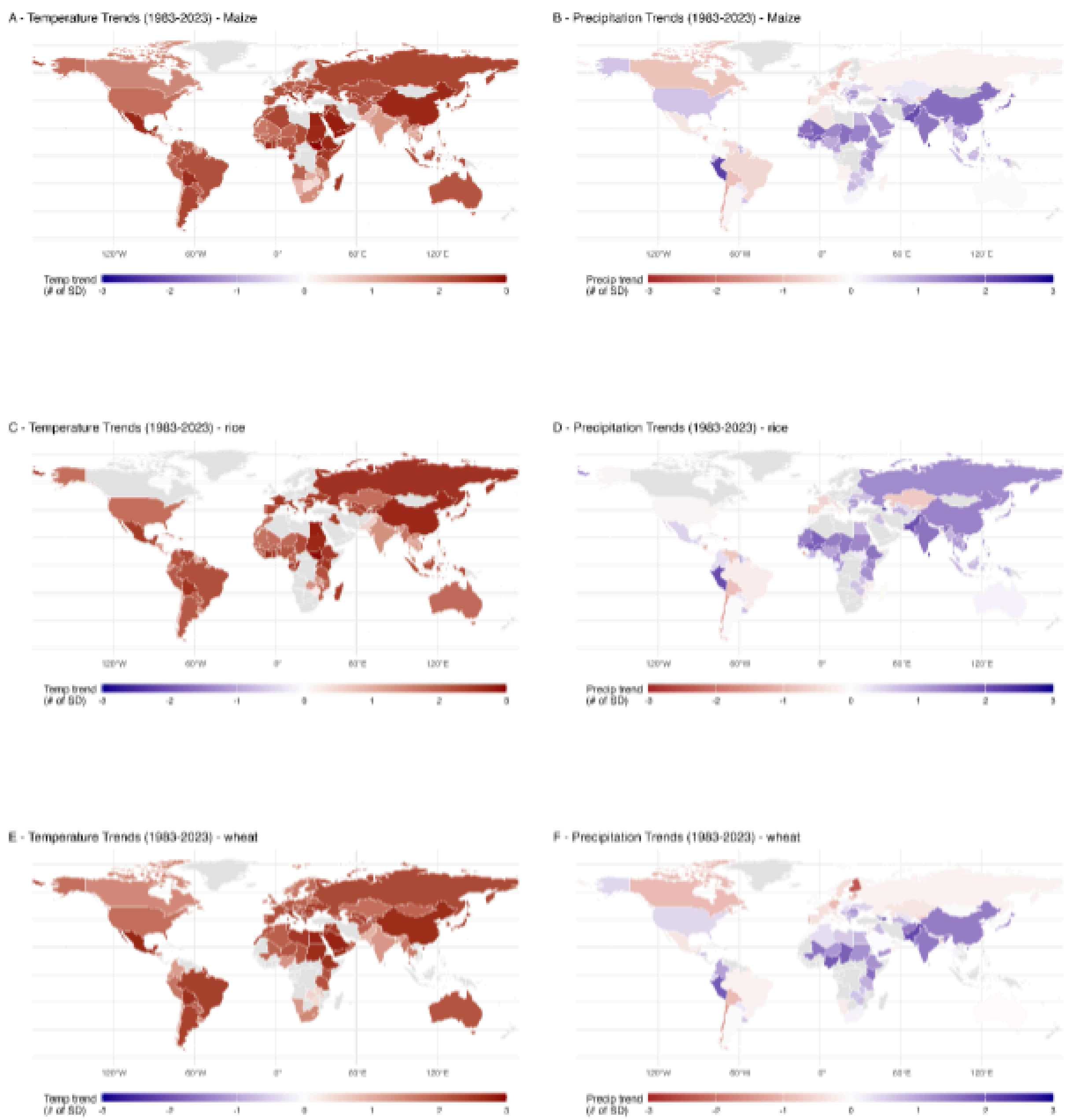


Figure 10. Climate trends by crop, 1983-2023.

areas represent countries with insufficient data for the given crop. Most major producing regions experienced warming trends exceeding one standard deviation, while precipitation trends show greater spatial heterogeneity with no consistent global pattern.

Against this backdrop, since 1990, average crop yields have steadily increased over time for most crops in the world. Figure 11 shows the evolution of yields for staple crops (top) including maize, rice, soybeans and wheat for the world (left) and for Africa (right). The lower figure panel displays yield trends for other cereals - fonio, millet, sorghum - and white roots and tubers - potato and cassava - for the world and Africa. Figure 12 shows the evolution of yields of a range of legumes and vegetables in Africa.

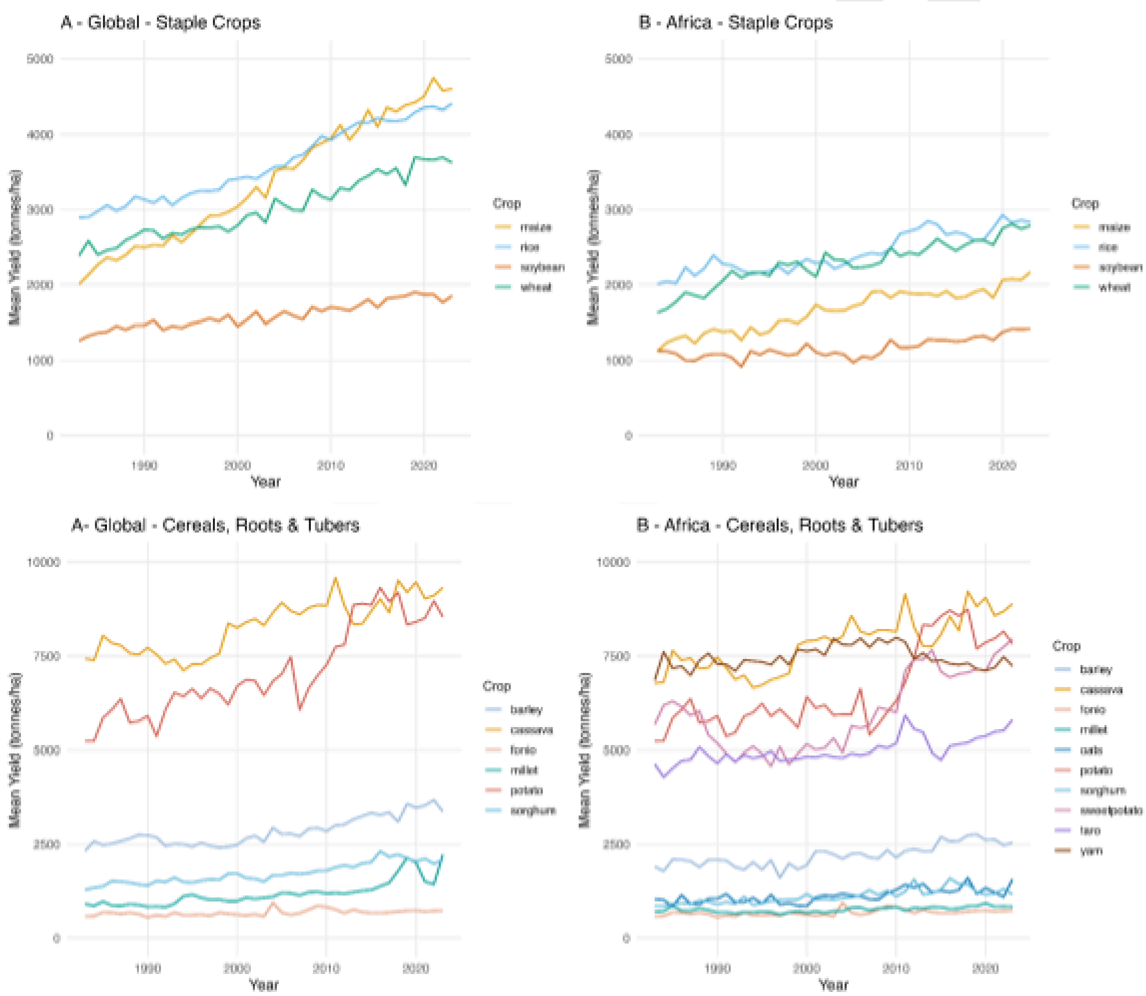


Figure 11. Evolution of yields for major crops for (left) the world and (right) Africa.

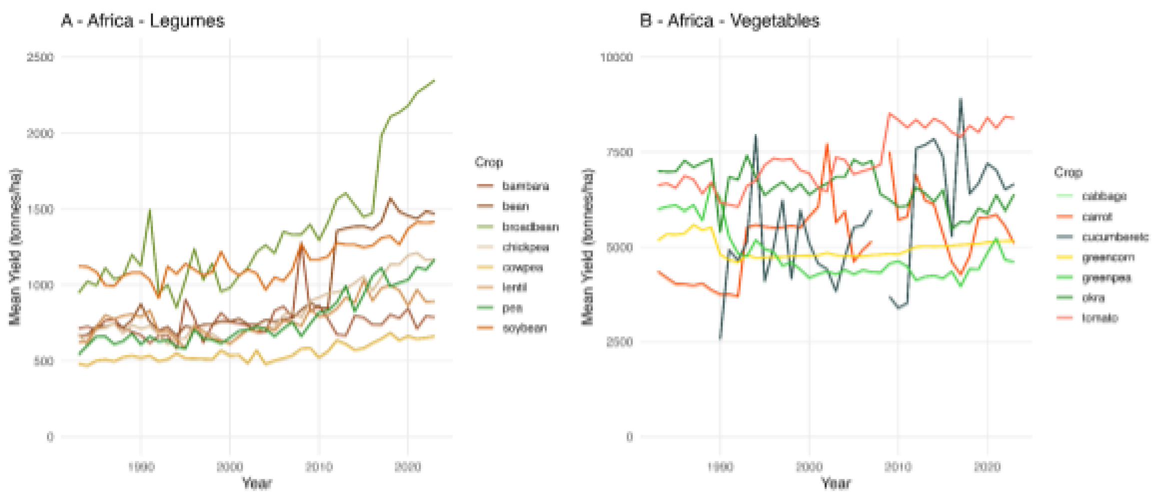


Figure 12. Evolution of African yields for (A) legumes and (B) vegetables.

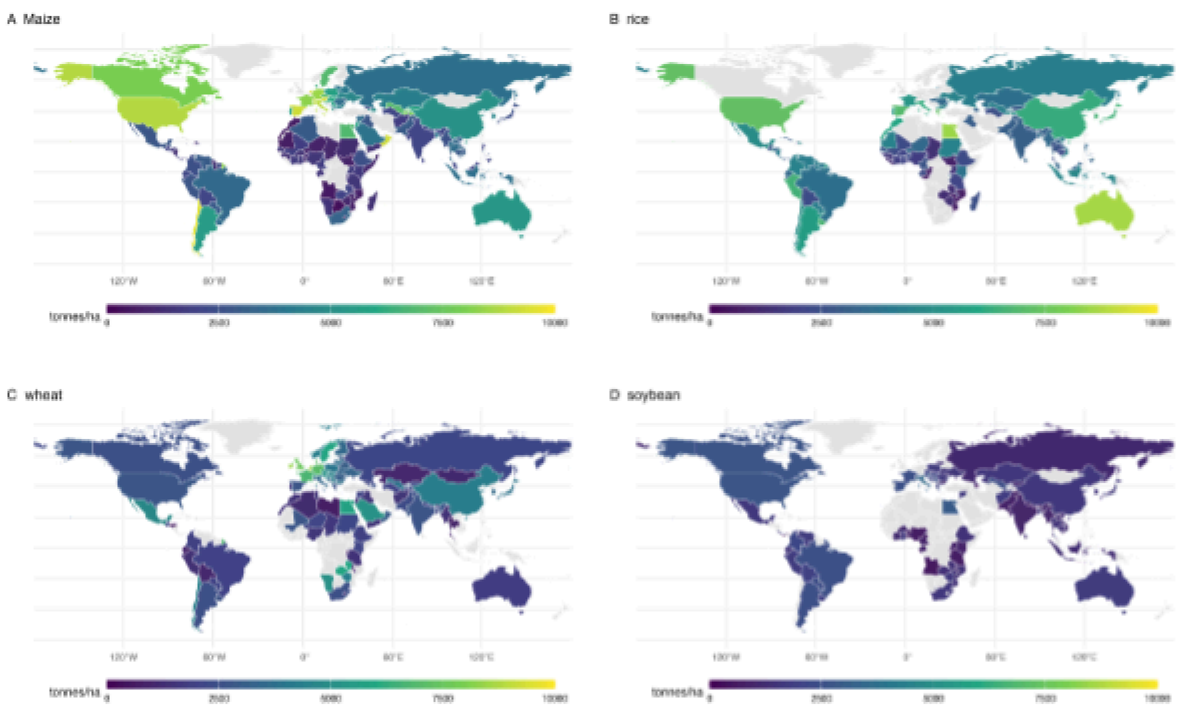


Figure 13. Mean yields for staple crops by country, 1983-2023 (tonnes/ha).

Figure 13 shows mean yields for staple crops by country over the 1983-2023 period for maize (A), rice (B), wheat (C), and soybean (D). For all staple crops, Africa shows the lowest average yields, typically below 2,500 kg/ha. In contrast, major producing regions in North America, Europe, and East Asia achieve substantially higher yields, often exceeding 5,000-7,500 kg/ha.

Figure 14 presents descriptive annual yield trends for the four major staple crops over the 1983-2023 period, calculated as the average percentage change in observed yields per year for each country-crop combination**.** Maize (Panel A) exhibits widespread yield improvements across much of South America, sub-Saharan Africa, and Asia, with annual growth rates typically ranging from +1% to +3% per year. Several African countries, however, show modest declines, likely reflecting ongoing challenges with soil degradation and climate variability. Rice (Panel B) displays strong positive trends across major Asian producers including China and India (+2% to +4% annually), indicating sustained productivity gains from the Green Revolution legacy, though some Southeast Asian and African nations show near-zero or negative trends. Wheat (Panel C) reveals notable heterogeneity, with substantial yield growth in Russia, Kazakhstan, and parts of Eastern Europe (+2% to +5%), while several African and Middle Eastern countries

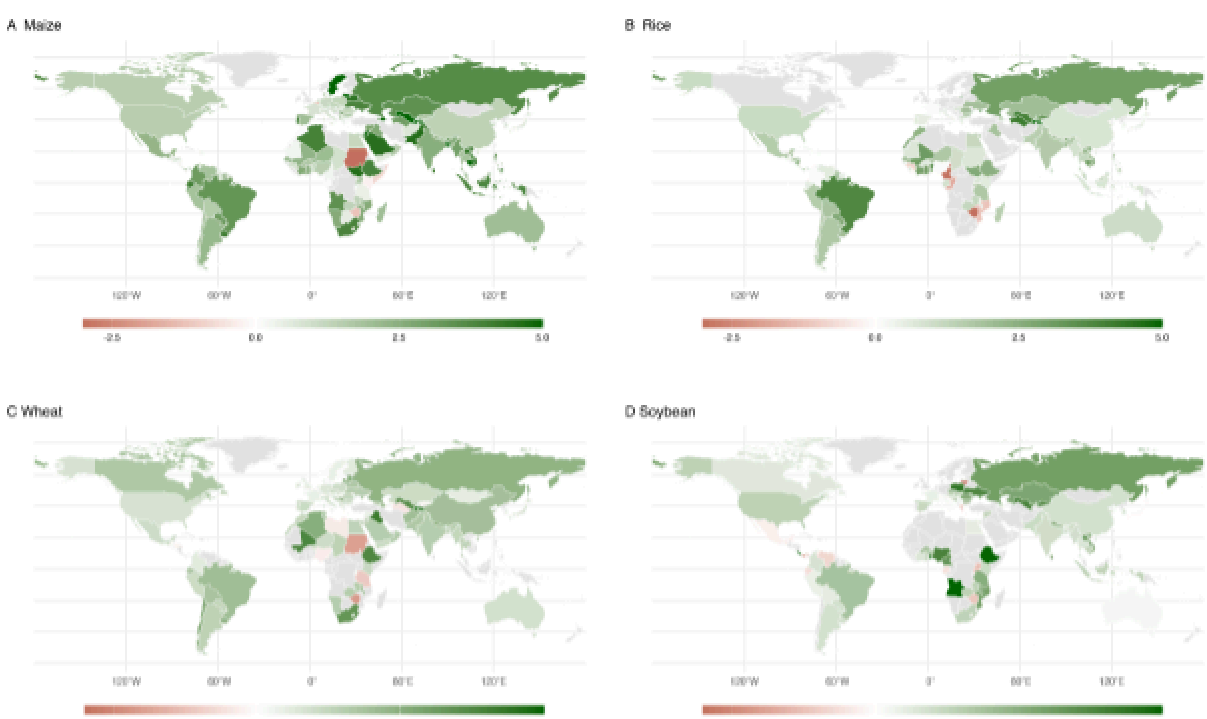


Figure 14. Estimated annual yield trends for 1983-2023 on crop yields by country.

experienced stagnation or decline. Soybean (Panel D) demonstrates robust yield increases in major producing regions including Brazil, Argentina, and the United States (+1.5% to +3%), with particularly strong trends in South America driven by technological advances and agricultural expansion. Overall, these maps reveal that most major producing regions achieved sustained yield improvements over the four-decade period, though important regional disparities persist, particularly in sub-Saharan Africa where some countries experienced stagnation or decline despite global productivity gains.

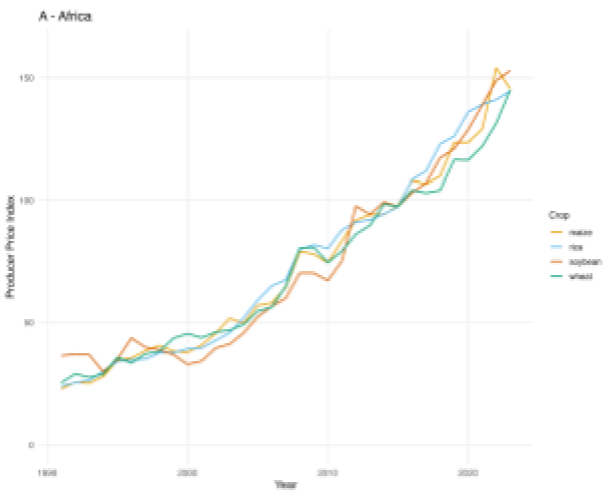


Figure 15. Evolution of selected crop prices over time (maize, rice, wheat and soybeans) in sub-Saharan Africa.

Figure 15 shows the evolution of annual prices[2] over time for main staple crops in African countries. Prices are PPI adjusted. Overall, for most countries and crops, prices seemed to have increased between 1980 and 2025 (see Appendix B for per country details).

Empirical Results: We find that climate trends from 1983 to 2023 have negatively impacted staple crop yields globally and in Africa, with temperature increases being the dominant driver (Figure 16 & 17), reinforcing prior work.[35,36] Temperature trends consistently reduced yields across all four staple crops, with soybean and maize experiencing the largest losses at approximately -2% to -2.5%, followed by wheat and rice at -1% to -1.5%. The net climate impact (gray bars) reveals soybean as the most vulnerable crop globally, with total yield reductions of around -1.5% to -2%, while maize shows similar negative impacts of -0.5% to -1%, and wheat and rice exhibit net impacts closer to zero as precipitation gains partially offset temperature losses. We see similar yield impacts for other cereals like barley (-3%), sorghum (-2%), and millet (-2%) African estimates (Figure 17B) show larger temperature effects for wheat and rice compared to global averages, while maize displays more favorable net impacts in Africa than globally, likely reflecting differences in precipitation trends. These results confirm that warming has been the primary constraint on crop productivity over the past four decades, with soybean, maize, and wheat demonstrating particularly high vulnerability to rising temperatures among the four major staple crops examined.

Figure 18 shows the net climate impact on staple crop yields from 1983 to 2023, expressed as percentage yield changes due to temperature and precipitation trends.

[2] Price data is trimmed at the 99th percentile (overall, not by country/crop). Price data selected is country/crop/year price data for which we have data on yields and weather.

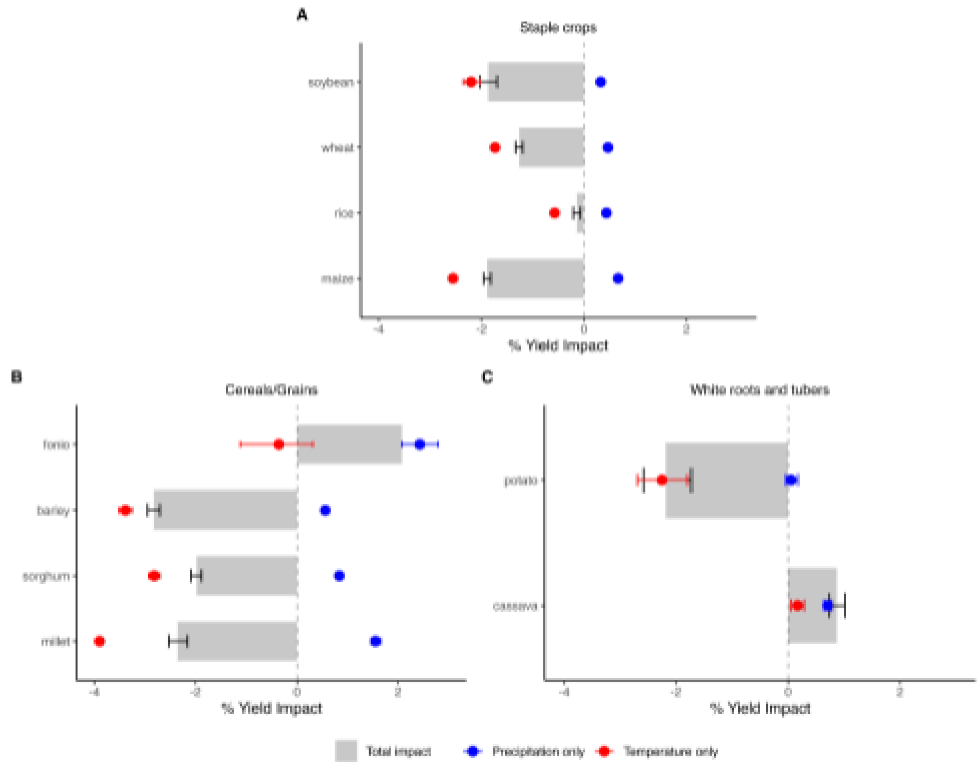


Figure 16. Estimated net impact of climate trends for 1983-2023 on crop yields for major producers and for global production for staple crops (A), cereals and other grains (B) and roots and tubers (C). Values are expressed as percent of average yield. Gray bars show median climate impact; error bars show 90% confidence intervals (5th to 95th percentiles) calculated from 500 bootstrap replications resampling countries with replacement. Red and blue dots show median estimate of impact of T trend and P trend, respectively.

Climate impacts are predominantly negative across major producing regions, with maize, wheat, and soybean experiencing the largest losses (-3% to -5%) in Russia, Central Asia, and parts of the Americas. Rice displays more heterogeneous patterns with mixed positive and negative impacts. The most severe climate damages appear in mid-to-high latitude regions experiencing rapid warming, while some tropical areas show neutral or slightly positive effects where precipitation increases have partially compensated for temperature stress. These patterns confirm that climate trends have been a net constraint on global crop productivity over the past four decades, with geographic and crop-specific heterogeneity reflecting differential sensitivities to warming and changing precipitation regimes.

Figure 19 shows the estimated net impact of climate trends for the 1983-2023 period on crop yields by country divided by the overall yield trend over 1983-2023. Negative values indicate that climate trends slowed yield trends, and positive values indicate that climate trends sped up yield trends, relative to what would have occurred without trends in climate. The wide variation reflects differences in both climate impacts and underlying yield growth rates, with the same absolute climate effect producing larger values in countries with slow agricultural progress. Maize (Panel A) exhibits predominantly negative values across North America, Russia, and Central Asia (-2 to -4 years), }

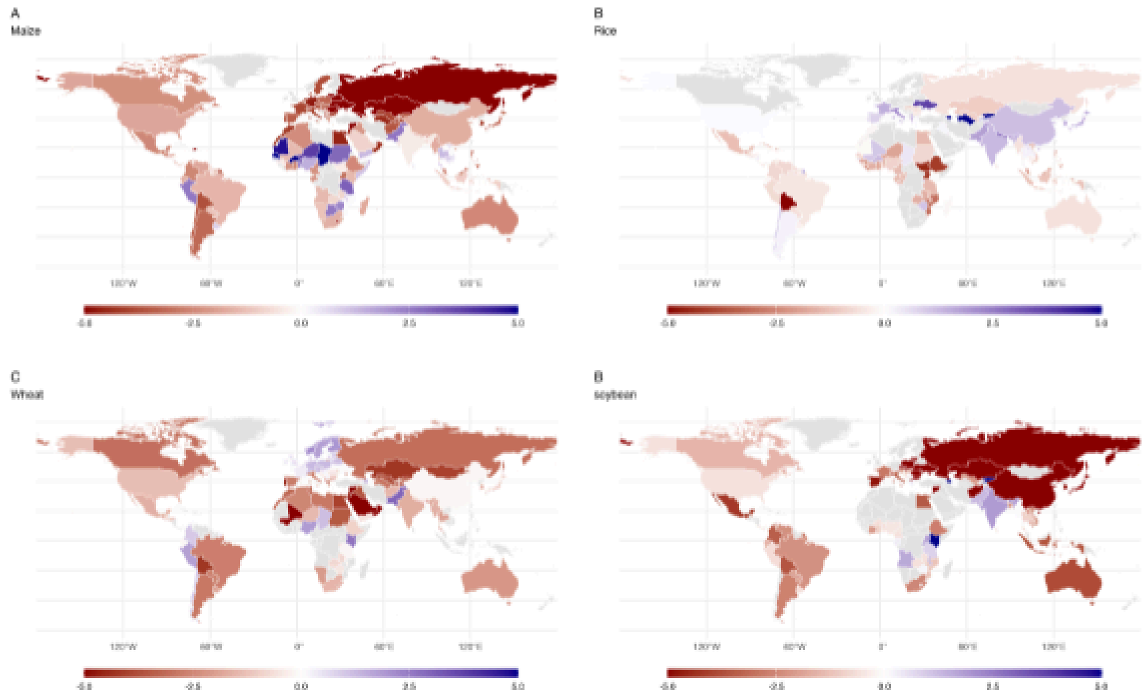


Figure 18. Estimated net impact of climate trends for 1983-2023 on crop yields by country. Values represent the total effect of temperature and precipitation trends on yields for staple crops.

indicating that climate trends substantially eroded agricultural progress in these major producing regions, while some African and Australian countries show modest positive values where favorable precipitation trends coincided with yield improvements. Rice (Panel B) displays the most heterogeneous patterns, with positive values across much of Asia and Europe suggesting climate trends enhanced productivity gains, contrasted with negative values in parts of Africa and Southeast Asia. Wheat (Panel C) reveals the most severe climate constraints, with deeply negative values across North America, Russia, Kazakhstan, and Australia (-3 to -4 years), reflecting both substantial warming impacts and relatively modest baseline yield growth in these regions. Soybean (Panel D) demonstrates widespread negative impacts, particularly severe in China, Russia, North America, and Australia (-3 to -4 years). The magnitude of these values reflects both climate impacts and baseline yield trends—as shown in the earlier yield trend maps (Figure Y), regions with stagnant productivity (+0% to +1% annually) like North America and Europe display disproportionately large negative values, while rapidly improving systems in South America and Asia show more moderate climate constraints despite similar absolute impacts.

Zooming in on Africa: Climate impacts on yields for diverse crops in Africa show substantial heterogeneity (Figure 17). Less common grains experienced varied impacts, with oats and barley suffering large losses (-7% and -5%) while fonio and millet remained near zero. These results align with prior work suggesting that grains native to the tropics show a lower sensitivity to extreme heat.[37] Roots and tubers native to the African continent even showed net positive effects from increasing temperatures, with gains for yam (+2.5%) and cassava (0.5%), while potato showed significant losses (-3%). These results reinforce findings from prior work that tropical root vegetables like cassava have strong potential as climate resilient crops.[38] Among pulses, broadbean was most severely affected (-9%), while most legumes showed modest impacts, and African crops again show the lowest heat sensitivity such as for cowpea (+1%) and bambara (+3%), two of the most common legumes in the African continent. We observe similar patterns for nuts and liquid oils where african nut tree crops like karite (+0.5%) and cashew (+2%) are significantly less impacted than almond (-2%), and coconut (+2%) is significantly less sensitive than olives (-8%). Vegetables displayed the greatest diversity in yield impacts, from large losses for carrot (-12%) and eggplant (-11%) to neutral impacts for tomato (+1%) and onion (+2%). These results reveal that climate vulnerability varies dramatically across crop types, with temperate-adapted species facing greater risks than tropical crops in African contexts. While these results highlight significant vulnerabilities for many crops, they also demonstrate clear opportunities for increasing resilience through crop diversification.

Climate and Prices: Although the signal of climate change on crop productivity emerges clearly from statistical analyses like the ones described above, a key question is the extent to which climate change has altered food prices. There are many compensatory mechanisms that might disrupt a standard supply-demand framework for food (i.e., when there is more of it, prices drop, when it becomes scarce, prices rise). To verify that our assumption that negative climate impacts translate into budget constraints (and vice versa), we explore the relationship between yields and prices using national accounts data. These results are summarized in Figure 20 (left). As countries' production increases, crop prices tend to decrease, consistent with a standard supply-and-demand framework: when supply rises (holding demand constant), prices fall. This pattern holds for the four crops, while significant for rice and wheat. Note that the table accounts for year-specific trends (things that are common across countries, like the rising food prices shown in Figure 15) and country-specific characteristics that are constant over time (like idiosyncrasies of individual national structures). Appendix B figure 2 shows the correlations between yields and prices by crop and country. (At the individual country level it is less clear that the assumptions of supplies linearly translating into price changes (and therefore how far a budget goes in terms of purchasing meals) always hold – the relationships vary widely across and within countries. This could be due to the influence of aid over the study period and other accounting idiosyncrasies, and suggest that detailed case studies with procurement staff over time could be especially valuable.)

We additionally examine the relationship between yield variations caused by climate disruptions and crop prices. In this analysis, rather than using observed yield variation, we use yield variation *predicted* by our model. The model allows us to isolate the component of yield variation attributable specifically to climate variability, abstracting from other factors. These results are shown in Figure 20 (right), and again we find a strong negative relationship between climate and prices, consistent with basic economic theory. Results show a negative relationship between yields and prices across all crops: a 1% increase in yield is associated with a 0.1-0.4% decrease in prices (Panel A), with stronger effects when using predicted yields (Panel B). This negative price-yield elasticity is stronger for wheat and rice : a 1% increase in yield decreases wheat prices by 0.4%, while a 1% increase in predicted yields decreases wheat prices by 1% and rice prices by 0.8%.

Figure 20. Statistical estimates of the relationship between changing crop yields and changing food prices. The left panel shows the relationship between prices and observed yields; the right panel shows the relationship between observed prices and predicted yields (that is, the component of yield that is determined by climate). Each dot is the result of a separate regression, conducted for that individual food product. Models include adjustment for crop type and country-specific features that might otherwise confound analysis.

Average Estimated Impacts (Thousands of Students Served per Year)			
Area	Students Served	Silent Cost of Climate	Regenerative Opportunity
Region			
East Asia & Pacific	14240	22.75	183.0
Europe & Central Asia	24940	80.06	444.0
Latin America & Caribbean	55770	414.30	2304.0
Middle East & North Africa	3528	43.04	225.6
North America	45700	222.50	910.7
South Asia	9847	29.95	632.5
Sub-Saharan Africa	69030	310.30	3264.0
Income Group			
LMIC	83400	290.90	3663.0
Non-LMIC	139700	832.00	4300.0
Global			
Total	223100	1123.00	7964.0

Table 4. Number of students served each year at present, and our estimated values for the silent cost of climate change and regenerative agricultural potential across those same programs.

Silent Cost of Climate Change on School Feeding Programs

When we link the library of climate impacts functions to information about what is served on each program's plate, we find that observed climate change to date has had an overall negative impact on school feeding programs. Under the assumptions described above, we estimate that at present, current program budgets would have been able to feed an additional 1.12 million students each year were global temperatures not rising. We call this the "silent cost of climate change" because this is not an effect that emerges suddenly (e.g., after a flood or drought), that would be instantaneously observable and straightforward to attribute. Instead, this is the longer run influence of rising temperatures and concomitant changing hydrological conditions that have - year over year - made crops on net marginally more difficult to produce than it *otherwise would have been* in the present day without historical warming.

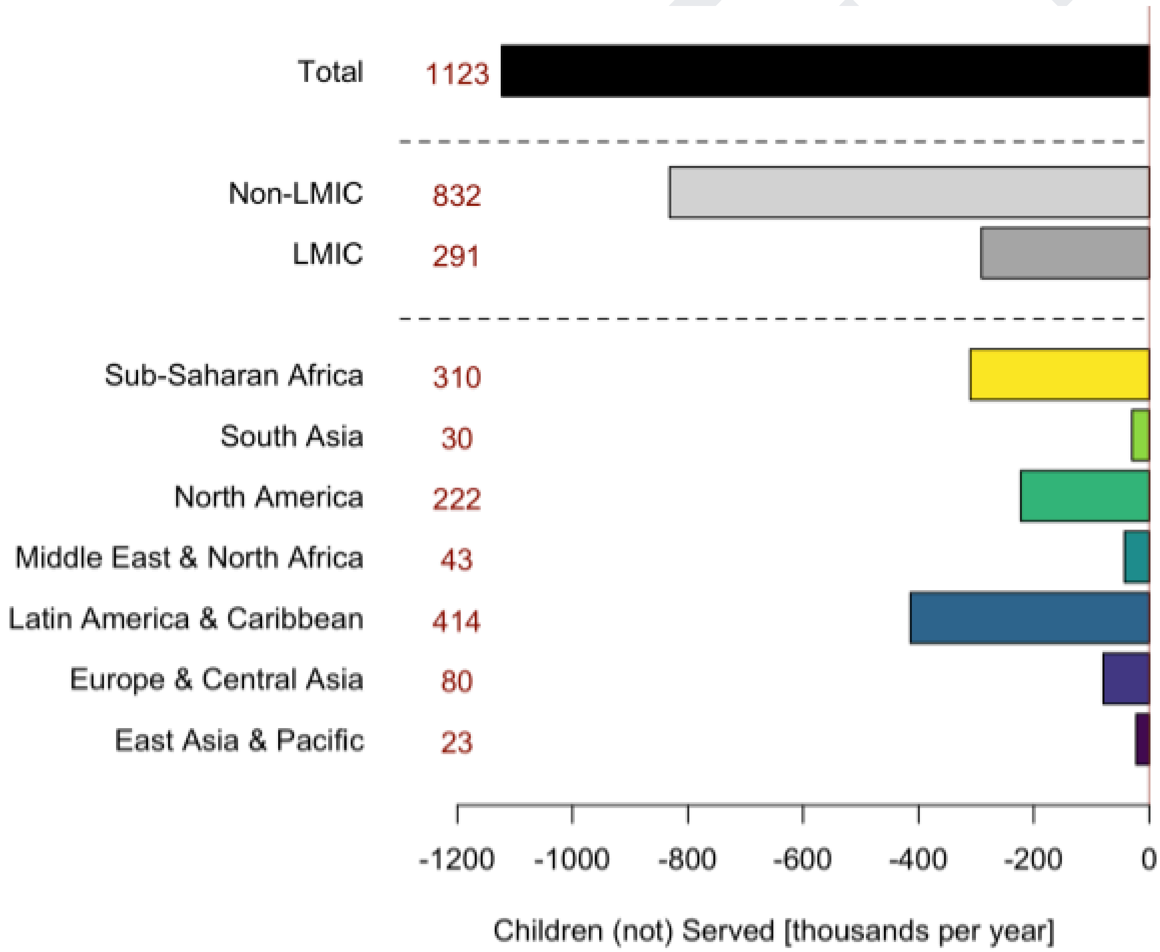


Figure 21. The Silent Cost of Climate Change on School Feeding Programs. Our analysis suggests that on current program budgets, an additional 1.12 million children per year could have been fed in the absence of climate change. These impacts are distributed globally (among the reporting programs), and across country income groups.

As shown in Figure 21, these impacts are distributed globally across the countries reporting to the Global Survey on School Feeding Programs, and affect both rich and poor countries alike. Although climate change has had mixed effects in different country-crop combinations, it is notable that on aggregate the effects to date have been negative. Moreover, these are the impacts due to *observed climate change*, and do not account for changes in the future, which – absent adaptation – would be expected to continue in the same direction. This highlights the urgent importance of adaptation in the agricultural systems that support school feeding programs, as well as consideration of climate risk more broadly by policymakers and program managers.

Regenerative Agriculture Potential of School Feeding Programs

When we link representative school plate data with projected yield impacts from regeneratively- versus conventionally-produced staple crops (rice, wheat, maize, and soybeans), we find that the overall potential for more resilient production globally is

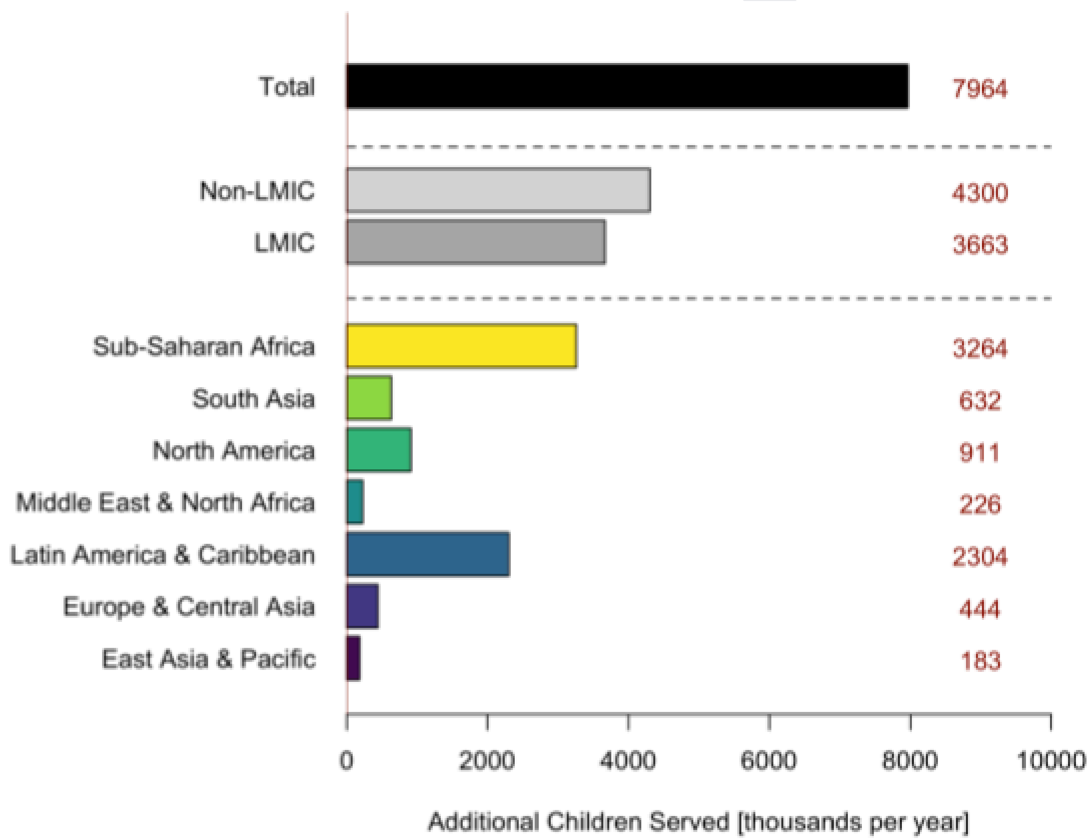


Figure 22. Potential Opportunity of Regenerative Grains in School Feeding Programs. Our analysis suggests that on current program budgets, nearly 8 million additional children per year could have been fed if global rice, wheat, maize, and soybeans were grown regeneratively. These impacts are distributed globally (among the reporting programs), and across country income groups.

large. Similar to the climate impacts analysis, not every crop in every location is expected to benefit from a yield boost from a switch to regenerative production; however, on net the impacts are large and positive. Globally we find that an additional 7.96 million children could be served on current program budgets under regenerative production practices. As shown in Figure 22, these impacts are distributed around the globe and across income groups.

In contrast with the Silent Cost of Climate Change estimates reported above, the regenerative agriculture potential estimates are projected (not derivable from observed patterns in-situ), and do not account for the costs of transitioning systems to be regenerative. However, they do represent findings from paired comparisons from experiments or trials that have mostly been conducted in present climate conditions. This means that the large positive impacts projected here are inclusive of climate change impacts to date, and can appropriately be interpreted as substantially exceeding existing adaptation gaps represented by the “Silent Cost” estimates.

We report mean values of the estimates in Figure 22 but note that the bounds on these projections are highly variable. In almost all cases they extend from zero or below zero to 2-3 times the mean estimates reported here. These wide bounds reflect the reality that the universe of regenerative agricultural trials remains small (for the purpose of studies like this). As noted in the methods section, the data we use combine multiple soil-preserving practices and pool experiments with different objectives to maximize statistical power. These results (and their wide bounds) highlight the need for larger scale regenerative trials across multiple climate zones, soil types, and crops to fully understand the potential of regenerative agriculture-supported school feeding programs and all of its nuances.

Scenario Analysis

Plate Composition

Our results demonstrate a large amount of variation in the sensitivity of different crops on our plate across food groups to climate change. A common theme across food groups is the superior climate resilience of many “orphan crops”.[39] We observe low to zero net reductions in yield from climate change for crops like fonio, cassava, yam, sweet potato, cowpeas, bambara relative to other grains, root vegetables, and legumes, which is particularly notable given significant projected crop yield reductions for crops like soybean and wheat. Though further work is needed to increase the precision of these estimates and better identify the mechanisms through which extreme weather reduces yield for these crops, it is clear that the variety of orphan crops offers farmers and consumers options for reducing exposure to climate risk.

There is a significant body of work highlighting the role of orphan crops in adapting to climate change. “Traditional and indigenous diets emphasize the use of locally sourced, seasonal ingredients, aligning with sustainable food practices. This entails the adoption of neglected and underutilized plant species and varieties, also known as “lost”, “native”, “orphan” and “indigenous”.[40] Our results demonstrating the climate resilience of many of these crops reinforces prior work that found lower sensitivity to heat and drought of orphan crops.[37] The crucial role of neglected crops as a way to solve both the food and climate crises, is increasingly being recognized, with the UN declaring 2023 the year of millet.[41] Others have also noted the potential of cassava in particular to ensure food security in a changing climate,[38] which aligns with our results finding that cassava, a starchy root vegetable grown mostly in Africa for thousands of years, is one of the most heat tolerant crops with major potential to increase climate resilience. The Vision for Adapted Crops and Soils, a state department program under the office of global food security from 2021-2025, attempted to increase research and investment in these crops.

Though more work needs to be done to quantify and actualize the potential of orphan crops to reduce the impacts of climate change on farmers and consumers, our results demonstrate that increasing the diversity of crops procured for school meals, particularly to African orphan crops like fonio, cassava, yam, cowpea, and karite, holds significant opportunity to reduce climate impacts on the cost of food for school meal programs. However, this will require more investment in the value chains for orphan crops, including improved seed varieties, irrigation, post-harvest processing and storage, as these value chains are not yet well-developed for many of these crops which show higher climate resilience.[42]

Potential Trade Impacts

So far, our analysis has focused on the impacts of climate and yield variations on food production with the assumption that these effects operate via domestic food prices faced by school feeding programs. However, this approach does not yet account for the role of trade in shaping these dynamics. There are two complementary ways to think about the role of trade in this system.

First, we can examine the relationship between international prices and domestic producer prices. As shown in Figure 23, international prices for key commodities tend to display different levels of volatility compared to country-specific producer prices. Countries can rely on international markets as a mechanism to smooth shocks, either after domestic production is disrupted, or in an anticipatory manner through procurement strategies that reduce exposure to expected risk. International procurement mechanisms for school feeding programs can thus help avoid sharp price fluctuations, though they may also involve trade-offs such as missing opportunities to purchase at temporarily lower prices when supplier flexibility is limited.

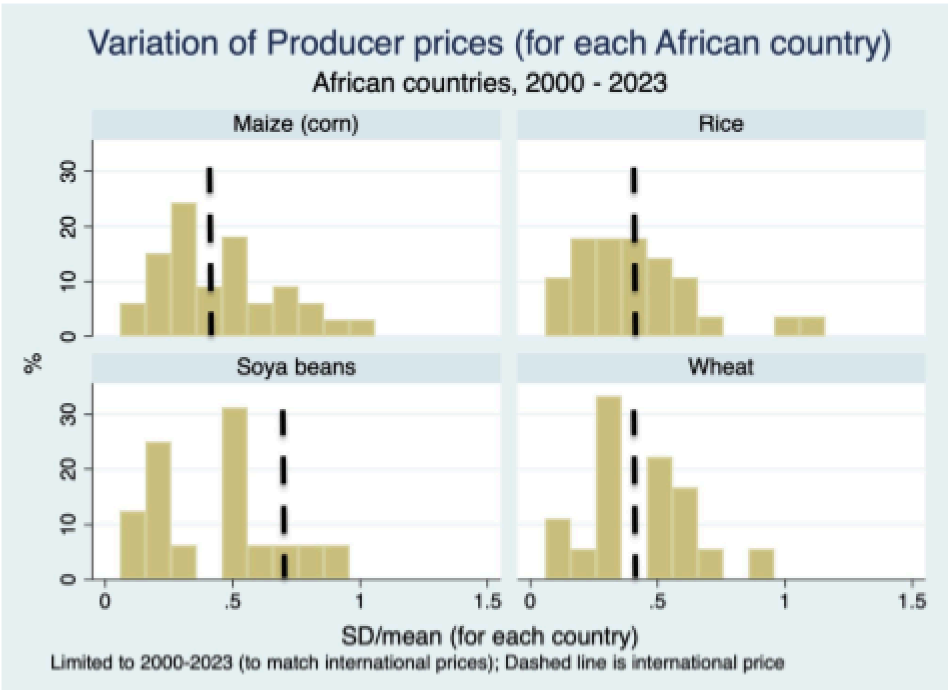


Figure 23. Variation in producer prices within African countries compared to variation in international prices, by major crop.

Second, with more detailed information on procurement we could extend the analysis presented here to explicitly include trade flows between countries. This would allow us to explore two important mechanisms:

1. Countries that are interconnected through trade may be affected by weather and yield shocks occurring elsewhere, as these shocks influence the supply and prices of imported goods.
2. Conversely, countries may insure themselves against domestic shocks by relying on imports from trade partners less affected by local conditions (or at minimum with climates and conditions that tend to be spatiotemporally unrelated).

This opens the door to a broader research agenda on how trade shapes resilience to climate and production shocks in school feeding programs. This includes understanding (i) how integrated different food economies are with each other and how weather-driven supply shocks propagate across borders and along supply chains, and (ii) exploring optimal trade portfolios that help mitigate risks. Such efforts would consider both crop diversification - for instance, incorporating more resilient crops, or a wider variety of production to supply year-round feeding programs - as well as trade partner diversification, or sourcing from countries with lower volatility or independent climate patterns.

Discussion

Contextualization with Case Studies

Four key points emerged across our case study discussions (see Appendix C for more detailed information). The first is that, in spite of the 'triple-win' potential for school feeding programs, most staff are focused on more immediate logistical concerns. By far, the biggest constraint and worry for most programs is budgetary. Cost per plate is very low, and there is perpetual concern about the commitment by governments to fund the school feeding programs, as well as concern (where applicable) about reliance on international organizations for funding.

Second, even where a stated program (or even policy priority) procurement from local farmers (benefitting rural development) is often more difficult than procuring from regional and international markets. Several program representatives stated that logistics, costs, and consistency tended to favor the latter. Relatedly, successful programs tend to be focused in urban areas where logistics is easier. The Central Kitchen model is more efficient, and makes it easier to monitor food quality and ensure food safety. Nevertheless, Brazil stands out as an example of success in a distributed/rural model as well.

Third, rice emerged as a surprisingly large component of school meals, often in stark contrast to the percentage of rice in the domestic food supply. Program staff emphasize that rice is easy to buy, store, transport, etc.; leveraging the very mature rice supply chains for centralized procurement alleviates a lot of concerns about the logistics of safely gathering, storing, and transporting other more local grains. More than one program also said that students prefer rice (it attracts kids to school). Even Brazil's program relies on rice as a primary staple (although it is sourced from Brazilian rice regions). The Kenya Food for Education program reported importing rice from Tanzania or at times India or Pakistan, depending on availability and geopolitics.

Finally, the case study (and especially the case study conversations) revealed that data from GCNF Global Survey and our methodology for inferring specific food products and amounts from the food frequency survey module don't always match what is actually on the plate for these major programs. Moreover, some of the assumptions about procurement may be a bit misleading in that (for example) some programs reported 100% domestic procurement, but were buying (e.g.) imported rice in domestic contexts. As such the value of in-depth conversations with program staff about what is actually served, how it is purchased, and what goes into such decisions are especially valuable for producing more accurate climate risk assessments for programs.

Plate Composition Implications for Nutrition and Climate

The composition of school meals varies substantially between countries and even between programs within countries. Two key findings emerge from analysis of school meal plates. First, we find overall limited food group diversity, especially in certain parts of Sub-Saharan Africa and Asia. Grains constitute about one-third of the estimated average ‘global plate’, and are typically paired with a legume and oil in the majority of programs. Vegetables are included in over half of programs, but are most commonly provided weekly or several times per week, with much fewer programs serving them daily, and some programs do not include any vegetables at all, as shown in the Kenya and Ethiopia case studies. While staple products can be fortified to help meet children’s micronutrient needs, this does not replace the need for providing a diverse, healthy plate. School meals are essential to meeting the nutritional requirements of many children globally, and can impact not just nutrition and health, but social and economic development outcomes, lifelong food habits, and sustainable agricultural production through procurement policies.[11] We find a substantial opportunity to improve the nutritional quality of school meal plates by providing a larger variety of nutrient-dense plant-based foods from diverse legumes, whole grains, vegetables, fruits, and moderate amounts of animal-source foods, particularly from sources like eggs, dairy, and fish/seafood, in line with healthy and sustainable diets.[15,16]

Second, we find a strong reliance on a limited number of crops, namely, maize, rice, wheat, and soya beans. All of these crops are climate sensitive, and we show a predicted decline in yield for all four crops globally and for rice, wheat, and soya beans in Sub-Saharan Africa. Furthermore, while our plate estimates show a relatively even distribution of wheat, rice, and maize, our expert consultation of select countries reveals a heavy reliance on rice, typically white rice. There is enormous potential for school meal procurement to serve as a catalyst for procurement of a wider variety of nutritionally-diverse, culturally relevant, and underutilized Indigenous crops.[11] Millets, encompassing various species of like pearl millet, finger millet, sorghum, fonio, and teff, are especially relevant to improving school meals in Africa and Asia; they are highly nutritious, with several species high in protein, iron, calcium, fiber, and other nutrients, grow well in dry and arid regions, and are a traditional crop that has been used across Africa and Asia.[41] A wider diversity of locally-relevant and nutritionally-dense legumes such as cow peas, pigeon peas, bambara beans, groundnuts, roots and tubers such as cassava, dark leafy green vegetables such as moringa, and fruits such as baobab, can also be included. Our findings provide further evidence that several of these crops are climate-resilient, including bambara beans, cowpeas, yams and cassava.

Emergent Issues

Through this research, several interesting issues emerged that would affect climate vulnerability and resilience analyses, but are beyond the scope of analysis of this report.

Rice: Many programs report using rice as a main staple in school meals even if it is not a primary domestic crop. This choice makes sense in many ways from a procurement and logistics perspective. The rice supply chain is mature, and the infrastructure to package, store, ship, and distribute rice is very well developed. By buying rice on international markets (or purchasing imported rice in domestic markets), programs are able to bring some predictability and stability to purchasing over the course of the year. However, rice itself introduces a new element of correlated risk to programs should they scale up in this model. International rice markets are thin (and thus inherently more susceptible to price swings). Although rice is one of the hardier crops at higher temperatures (e.g., Figures 16 & 17), it remains quite vulnerable to larger modes of climate variability like the El Niño Southern Oscillation (ENSO). El Niño years tend to cause droughts in a number of key rice producing regions, causing stiffer competition for international purchases in those times.

Correlated shocks: A related but more general note is that reliance on imported products (whether procured on international markets or in domestic markets) can bring with it some elements of resilience (like storage, safety, etc.), but can introduce correlated vulnerabilities to the school feeding program social safety net. If many programs rely on exports from the same region, they are vulnerable to climate (or other) shocks to that source system. By working directly with program procurement directors, analysis could be tailored to help individual programs develop resilience across their domestic and international procurement portfolios, and to develop secondary plans for food supplies if first choice systems or trading partners experience disruptions.

Food Safety: Discussions with case study program representatives echoed an issue that has appeared in international news media in recent months – food safety. After thousands of children in Indonesia have been sickened in multiple waves of food poisoning via school meals, the flagship nationwide program in Indonesia is in serious jeopardy. Food safety is related to climate risk, and procurement and production conditions directly interact with the ultimate safety of meals served to children. The merits of distributed procurement and preparation models versus central kitchen models are currently being considered around the world. Detailed studies with individual programs could more concretely incorporate the food safety dimension of risk/resilience into climate-smart program design.

Price Tradeoffs: Finally, most programs are spending less than $1 USD per child per day for school meals, with 50% under $0.30 per child per day (based on 180 days). These levels of funding leave very small margins for change that might raise costs either directly (more expensive products) or indirectly (switching to products that raise operational costs, for example). Climate risk and resilience in the school meals landscape cannot be understood without better information about the wraparound services that support such programs and their costs (transportation, energy costs for cooking, etc.); it is clear that the true win-win solutions will be ones that can help lower (and stabilize) system costs (not just food).

Limitations and Future Research Needs

Plate composition: As we note in the case studies, our estimated school meal plate composition is not per se what is provided in practice. We use countries' total food supply as the basis for estimating crop portfolios within each given food category. This approach introduces a margin of error since it does not reflect procurement decisions made by school meal staff. Nevertheless, we use this method as a best-guess, systematic, and replicable approach to understanding crop proportions for each country. Our estimates also do not include animal-source foods as estimating climate and regenerative impacts on egg, dairy, fish/seafood, and meat production is not straightforward and lacks insufficient standardized data.

Future iterations of the Global Survey of School Meal Programmes could consider adding a short food frequency questionnaire in addition to querying food groups to determine the composition of school meal plates at a more granular scale. This type of data would provide a comprehensive picture of the state of school feeding programs globally, which currently is possible only through studies of individual programs, and has the potential to be useful to researchers, practitioners, and policy-makers alike.

Estimating Climate Impacts on Crop Yields: To estimate our climate damage functions, or the impacts of temperature and precipitation on crop yields, we follow a similar approach to the one taken in earlier work[35], assuming that we can simply use mean temperature and total precipitation during the growing season to identify the impact of climate on crop yields. However, we know that this assumption is false because each crop responds differently to extreme temperatures and precipitation. For example, wheat has a senescence period during which it is especially sensitive to extreme heat, and ignoring this leads to underestimates of the true impact of extreme heat on wheat yields.[43] In addition, for diverse African crops, we use annual temperature and precipitation because of limited data on growing seasons. Yearly (soon to be growing-season) average precipitation may not capture critical changes in rainfall patterns. Positive or neutral precipitation trends can mask increased variability, more frequent dry spells, or shifts in rainfall timing—all of which can harm crop yields even when total seasonal precipitation remains stable or increases.[44] Similarly, our use of average temperature may understate the importance of extreme heat events, which can cause disproportionate yield losses during sensitive growth stages.

This problem becomes especially urgent as we expand our analyses beyond the four main staple crops to legumes, roots and tubers, fruits, vegetables, etc. Though these are often referred to as "specialty crops" or "orphan crops", we know they are a large fraction of the total calories consumed in large regions of the global south.[39] Moreover, food security also encompasses nutrition, so estimating the impacts of climate change on food security requires quantifying the impacts of climate change on legumes, roots and tubers, fruits, and vegetables, as these foods constitute the majority of a healthy diet.[45] So far, little large-scale empirical work has been done to understand the impacts of climate change on the yields of these crops. This is a huge gap as we not only do not know how much climate change reduces yields for these crops, we don't even know the mechanisms through which climate change impacts yields for these crops. Are fruit tree crops most impacted by extreme weather during fruiting season, or throughout the year? Are roots and tubers like cassava and potatoes more heat tolerant than other crops because they are grown underground? How does climate sensitivity vary among the wide diversity of vegetables grown in the global south? Answers to these questions will not only help us understand the impacts of climate change on food security, they will point the way to adaptation solutions across a wide diversity of crops such as varying planting dates, timing irrigation to aid during more sensitive crop stages, and switching to more resilient crops and plant varieties.

In future work, we hope to bridge the gap in climate damage functions for diverse crops by combining global crop yield data from FAO with weather data from satellites and climate models we used in this report to get accurate estimates of climate change on crop yields for >100 crops. First, we intend to expand the crop coverage in our global analysis and refine our approach by focusing on country-specific growing seasons for each crop. Second, we plan to decompose yield impacts into contributions from time trends, seasonal variations, covariate shocks, and idiosyncratic shocks, following another methodological approach.[46] We will then systematically evaluate a larger diversity of different specifications of weather data and evaluating their out-of-sample prediction error to understand exactly *how* climate impacts crop yields for each crop, following a recent study.[31] Using this approach, we believe we can estimate the impact of climate change on crop yields for a much wider diversity of crops (6 crop types → >100 crop types) than has been previously addressed by existing work.

Estimating Climate Impacts on Food Prices: To estimate the effect of climate change on food prices, we examine the relationship between crop yields and food prices and combine them with our estimates of climate impacts on crop yields, following the approach taken in previous work.[47] However, there are four important limitations of this approach: 1) Total food production depends on more than just crop yields 2) Farmgate prices do not capture variation in end product prices driven by post-harvest factors 3) Food prices depend on changes in demand as well as changes in supply. (4) Markets are (at least partially) integrated and trade plays a major role in affecting food prices. We describe these limitations as well as how we plan to address them in future work below.

Total production for a given crop depends on the product of three components: crop yields or the amount of tons per hectare, harvested area or total area on which the crop is grown, and harvest index or the percentage of crop production that can be sold, and the reality is that climate change has significant impacts on all three. Climate change can reduce the yields of crops because of extreme heat, drought, or floods, which we cover in this report. Climate change also impacts the total harvested area because of reduced water availability or crop suitability. Climate change also impacts harvest indices through reductions in quality or increased damages. In future work, we plan to use similar datasets to the crop yield data used in this report on harvested area and harvest indices to apply similar econometric approaches to identify the impact of climate change on harvested area and harvest indices, allowing us to get a full picture of the impacts of climate change on crop production.

The farmgate price is not the same as the price the end consumer pays (whether individual school kitchens or school feeding programs in our context), The difference can be attributed to efficiency of components of the post-harvest value chain including storage, processing, transportation, distribution, and marketing. Particularly in developing countries, there are huge opportunities to increase the stability of food prices by investing in storage facilities to smooth prices[48], renewable energy processing facilities such as solar dryers to reduce waste,[49] and solar cold storage to improve access to fresh fruits and vegetables.[50] In future work we hope to investigate the impact of such investments on improving price stability.

We build our estimates on the relationship between crop production and crop prices, but prices are of course the result of the combination of supply and demand, and demand remains a hidden confounding variable in our analysis as we've currently framed it. In future work, we aim to improve estimates of the impacts of supply shocks on prices with demand modelling.[51] And, as highlighted above, trade needs to be included in the analysis.

Regenerative Agricultural Potential: Our research into regenerative agricultural potential suggest a tremendous information gap. More side-by-side comparisons of more crops in more regions would help drive down the uncertainty for regenerative agriculture's potential. This would have a two-fold effect on the current knowledge base: first, it would enable the harmonization of study metrics and reporting, and would enable researchers to stiffen the criteria for inclusion in meta-analyses like the one we use here. The coalition of actors working to understand and implement regenerative school meals could have tremendous research and practical impact by seeding a set of structured regenerative agriculture trials that compare soil health, productivity (yield), other regenerative outcomes, *and* account for the costs of transitioning systems. Information on variation in yields in regenerative systems is almost nonexistent (most trials have not run long enough) - but such information is exceedingly important and reliability could be the most important dimension of change that healthier soils bring to the agricultural systems supporting school feeding programs. Finally, while we focused on yields here, we note that some of the benefits of regenerative agriculture may be in soil, system, and community health – even if yields are unchanged.

Conclusions

Here we highlight two new findings about school feeding programs around the world. First, our analysis shows that school feeding programs are not immune to the pressures climate change has exerted on global agricultural systems and that – as a result, in the present day – program budgets do not go as far as they would have in a stable climate. We estimate that these climate impacts are the equivalent of 1.12 million school children per year who are not being served. We also find that a production shift to regeneratively-produced major staples (compared to conventional) would boost productivity and through greater availability (and lower prices) provide meals for an additional 7.96 million children per year in current programs on current budgets. These two metrics – along with considerations noted here about nutrition, trade, and cost – are a starting point for advising school meal programs about climate risk and provide a framework for thinking about resilience in both the short and long term.

References

1. Cooper, Matthew W *et al.* Mapping the effects of drought on child stunting | PNAS. *Proc. Natl. Acad. Sci.* **116**, 17219–17224 (2019).

2. Thiede, B. C. & Strube, J. Climate variability and child nutrition: Findings from sub-Saharan Africa. *Glob. Environ. Change* **65**, 102192 (2020).

3. Anttila-Hughes, J. K., Jina, A. S. & McCord, G. C. ENSO impacts child undernutrition in the global tropics. *Nat. Commun.* **12**, 5785 (2021).

4. Ansah, I. G. K., Gardebroek, C. & Ihle, R. Shock interactions, coping strategy choices and household food security. *Clim. Dev.* **13**, 414–426 (2021).

5. *Nutrition Action in Schools: A Review of Evidence Related to the Nutrition-Friendly Schools Initiative*. https://www.who.int/publications/i/item/9789241516969.

6. Gelli, A. & Daryanani, R. Are School Feeding Programs in Low-Income Settings Sustainable? Insights on the Costs of School Feeding Compared with Investments in Primary Education. *Food Nutr. Bull.* **34**, 310–317 (2013).

7. Spill, M. K. *et al.* Universal Free School Meals and School and Student Outcomes: A Systematic Review. *JAMA Netw. Open* **7**, e2424082 (2024).

8. Bundy, D. *et al.* Re-Imagining School Feeding : A High-Return Investment in Human Capital and Local Economies. *Minist. Educ.* https://repositorio.minedu.gob.pe/handle/20.500.12799/6582 (2018).

9. Verguet, S. *et al.* The Broader Economic Value of School Feeding Programs in Low- and Middle-Income Countries: Estimating the Multi-Sectoral Returns to Public Health, Human Capital, Social Protection, and the Local Economy. *Front. Public Health* **8**, (2020).

10. Elinder, L. S., Eustachio Colombo, P., Patterson, E., Parlesak, A. & Lindroos, A. K. Successful Implementation of Climate-Friendly, Nutritious, and Acceptable School Meals in Practice: The OPTIMAT™ Intervention Study. *Sustainability* **12**, 8475 (2020).

11. Pastorino, S. *et al.* School meals and food systems: Rethinking the consequences for climate, environment, biodiversity, and food sovereignty. https://doi.org/10.17037/pubs.04671492 (2023) doi:10.17037/pubs.04671492.

12. Franco, M., Díez, J., Vidal, I., Cohen, N. & Batalla, I. Universal, healthy and sustainable school meals: An opportunity for impactful food and climate research. *PLOS Clim.* **4**, e0000676 (2025).

13. Global Report of School Meal Programs Around the World. *GCNF* https://gcnf.org/global-reports/.

14. Results from the 2024 Global Survey of School Meal Programmes | School Meals Coalition. https://schoolmealscoalition.org/results-2024-global-survey-school-meal-programmes

15. Pastorino, S. *et al.* Planet-friendly school meals: opportunities to improve children's health and leverage change in food systems. *Lancet Planet. Health* **0**, (2024).

16. Springmann, M., Hansoge, M. P., Schulz, L., Pastorino, S. & Bundy, D. A. P. The health, environmental, and cost implications of providing healthy and sustainable school meals for every child by 2030: a global modelling study. *Lancet Planet. Health* **0**, (2025).

17. Global Report of School Meal Programs Around the World. *GCNF* https://gcnf.org/global-survey/.

18. FAO, F. and A. O. of the U. N. FAOSTAT Statistical Database. (1997).

19. Tang, F. H. M. *et al.* CROPGRIDS: a global geo-referenced dataset of 173 crops. *Sci. Data* **11**, 413 (2024).

20. ERA5-Land monthly averaged data from 1950 to present. https://cds.climate.copernicus.eu/datasets/reanalysis-era5-land-monthly-means?tab=overview.

21. Peterson, P. *et al.* The Climate Hazards Group InfraRed Precipitation with Stations (CHIRPS) v2. 0 Dataset: 35 year Quasi-Global Precipitation Estimates for Drought Monitoring. in vol. 2015 NH41D-05 (2015).

22. Tamburini, G. *et al.* Agricultural diversification promotes multiple ecosystem services without compromising yield. *Sci. Adv.* **6**, eaba1715 (2020).

23. Rasmussen, L. V. *et al.* Joint environmental and social benefits from diversified agriculture. *Science* **384**, 87–93 (2024).

24. Romero Antonio, M. E., Faye, A., Betancur-Corredor, B., Baumüller, H. & von Braun, J. Productivity effects of agroecological practices in Africa: insights from a systematic review and meta-analysis. *Food Secur.* **17**, 207–229 (2025).

25. Beillouin, D., Ben-Ari, T., Malézieux, E., Seufert, V. & Makowski, D. Positive but variable effects of crop diversification on biodiversity and ecosystem services. *Glob. Change Biol.* **27**, 4697–4710 (2021).

26. Encarnation, D. G., Powell, R. S., Smith, P. & Pellegrini, A. F. A. Identifying win-win opportunities and trade-offs for sustainable agriculture to improve agricultural productivity and soil carbon sequestration: A global meta-analysis. *bioRxiv* 2025.09.02.673637 (2025) doi:10.1101/2025.09.02.673637.

27. Dittmer, K. M. *et al.* Agroecology Can Promote Climate Change Adaptation Outcomes Without Compromising Yield In Smallholder Systems. *Environ. Manage.* **72**, 333–342 (2023).

28. Paut, R., Garreau, L., Ollivier, G., Sabatier, R. & Tchamitchian, M. A global dataset of experimental intercropping and agroforestry studies in horticulture. *Sci. Data* **11**, 5 (2024).

29. The Nature Conservancy. AgEvidence - the impact of agricultural practices on crops and the environment. https://www.agevidence.org/.

30. Bezner Kerr, R. *et al.* Food, Fibre, and Other Ecosystem Products. *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (2022) doi:10.1017/9781009325844.007.

31. Hultgren, A. *et al.* Impacts of climate change on global agriculture accounting for adaptation. *Nature* **642**, 644–652 (2025).

32. Indicators for assessing infant and young child feeding practices: part 2 measurement. https://www.who.int/publications/i/item/9789241599290.

33. Guidelines for measuring household and individual dietary diversity | Agrifood Economics | Food and Agriculture Organization of the United Nations. https://www.fao.org/agrifood-economics/publications/detail/en/c/122321/.

34. Nutrition Questionnaire Service Center | Department of Nutrition | Harvard T.H. Chan School of Public Health. https://hsph.harvard.edu/department/nutrition/nutrition-questionnaire-service-center/ (2024).

35. Lobell, D. B., Schlenker, W. & Costa-Roberts, J. Climate Trends and Global Crop Production Since 1980. *Science* **333**, 616–620 (2011).

36. Schlenker, W. & Roberts, M. J. Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proc. Natl. Acad. Sci.* **106**, 15594–15598 (2009).

37. DeFries, R. *et al.* Climate resilience of dry season cereals in India. *Sci. Rep.* **13**, 9960 (2023).

38. Jarvis, A., Ramirez-Villegas, J., Herrera Campo, B. V. & Navarro-Racines, C. Is Cassava the Answer to African Climate Change Adaptation? *Trop. Plant Biol.* **5**, 9–29 (2012).

39. Naylor, R. L. *et al.* Biotechnology in the developing world: a case for increased investments in orphan crops. *Food Policy* **29**, 15–44 (2004).

40. IFPRI. Bringing back neglected crops: A food and climate solution for Africa. https://www.ifpri.org/blog/bringing-back-neglected-crops-food-and-climate-solution-africa/ (2023).

41. FAO. *Unleashing the Potential of Millets*. http://www.fao.org/documents/card/en/c/cc7484en (2023) doi:10.4060/cc7484en.

42. Mabhaudhi, T. *et al.* Prospects of orphan crops in climate change. *Planta* **250**, 695–708 (2019).

43. Lobell, D. B. The case of the missing wheat. *Environ. Res. Lett.* **7**, 021002 (2012).

44. Polonik, P., Ricke, K. & Burney, J. Estimating the impacts of climate change: reconciling disconnects between physical climate and statistical models. *Clim. CHANGE* **178**, (2025).

45. Rockström, J. *et al.* The EAT–Lancet Commission on healthy, sustainable, and just food systems. *The Lancet* **406**, 1625–1700 (2025).

46. Burney, J., McIntosh, C., Lopez-Videla, B., Samphantharak, K. & Gori Maia, A. Empirical modeling of agricultural climate risk. *Proc. Natl. Acad. Sci.* **121**, e2215677121 (2024).

47. Hertel, T. W., Burke, M. B. & Lobell, D. B. The poverty implications of climate-induced crop yield changes by 2030. *Glob. Environ. Change* **20**, 577–585 (2010).

48. Burke, M., Bergquist, L. F. & Miguel, E. Sell Low and Buy High: Arbitrage and Local Price Effects in Kenyan Markets*. *Q. J. Econ.* **134**, 785–842 (2019).

49. Machala, M. L., Tan, F. L., Poletayev, A., Khan, M. I. & Benson, S. M. Overcoming barriers to solar dryer adoption and the promise of multi-seasonal use in India. *Energy Sustain. Dev.* **68**, 18–28 (2022).

50. Makule, E., Dimoso, N. & Tassou, S. A. Precooling and Cold Storage Methods for Fruits and Vegetables in Sub-Saharan Africa—A Review. *Horticulturae* **8**, 776 (2022).

51. McFadden, D. *et al.* Demand model estimation and validation. *Urban Travel Demand Forecast. Proj. Phase* **1**, (1977).

Appendix A: Empirical Methods Details - Climate Impacts on Yields

To estimate the effects of climate on yields, we estimate the following model using log-transformed yields following [Lobell et al., 2011] :

$$Log(Y_{i,t}) = c_i + d_{1i} * year + d_{2i} * year^2 + \beta X_{i,t} + \epsilon_{i,t}$$

With c_i country fixed effect, d_{1i} the country-specific linear time trend and d_{2i} the country-specific quadratic time trend, β a vector of coefficients associated to the variables $T,\ T^2, P,\ P^2$. To mitigate noise in the yield data, we removed crop–country time series exhibiting three or more occurrences of identical FAO yield values in successive years.

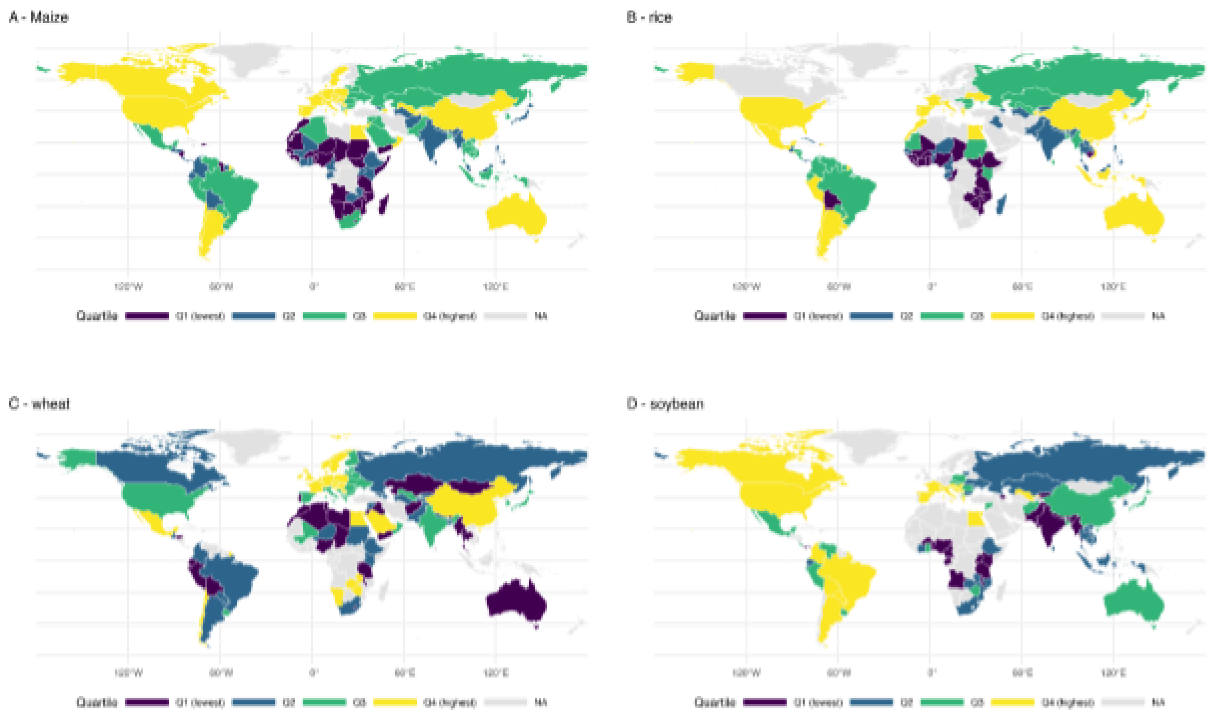
The effect of long-term climate trends on yields was estimated through a four-step procedure. Let consider :

- $T^*_{i,t}$ = predicted temperature for country *i* and year *t*, obtained from a linear trend fitted over 1983–2023.
- $Td_{i,t}$ =detrended temperature = $T_{i,t} - T^*_{i,t} + T^*_{i,1983}$

Using these variables, we apply the regression model F(T,P)F(T, P)F(T,P) to generate:

(i) $F(T, P) =$ predicted yields with observed temperature and precipitation
(ii) $F(Td, P) =$ predicted yields with detrended temperature and observed precipitation
(iii) $F(T, Pd) =$ predicted yields with observed temperature and detrended precipitation
(iv) F(Td,Pd) = predicted yields with detrended temperature and precipitation

We then calculate the trends in the yield differences between (i) and (ii), (i) and (iii), and (i) and (iv) to isolate the contribution of temperature, precipitation, and combined climate trends, respectively. Confidence intervals (5th–95th percentiles) were estimated using bootstrap resampling of country-crop observations with replacement (500 replications), which captures sampling uncertainty in the climate impact estimates conditional on the estimated damage functions.

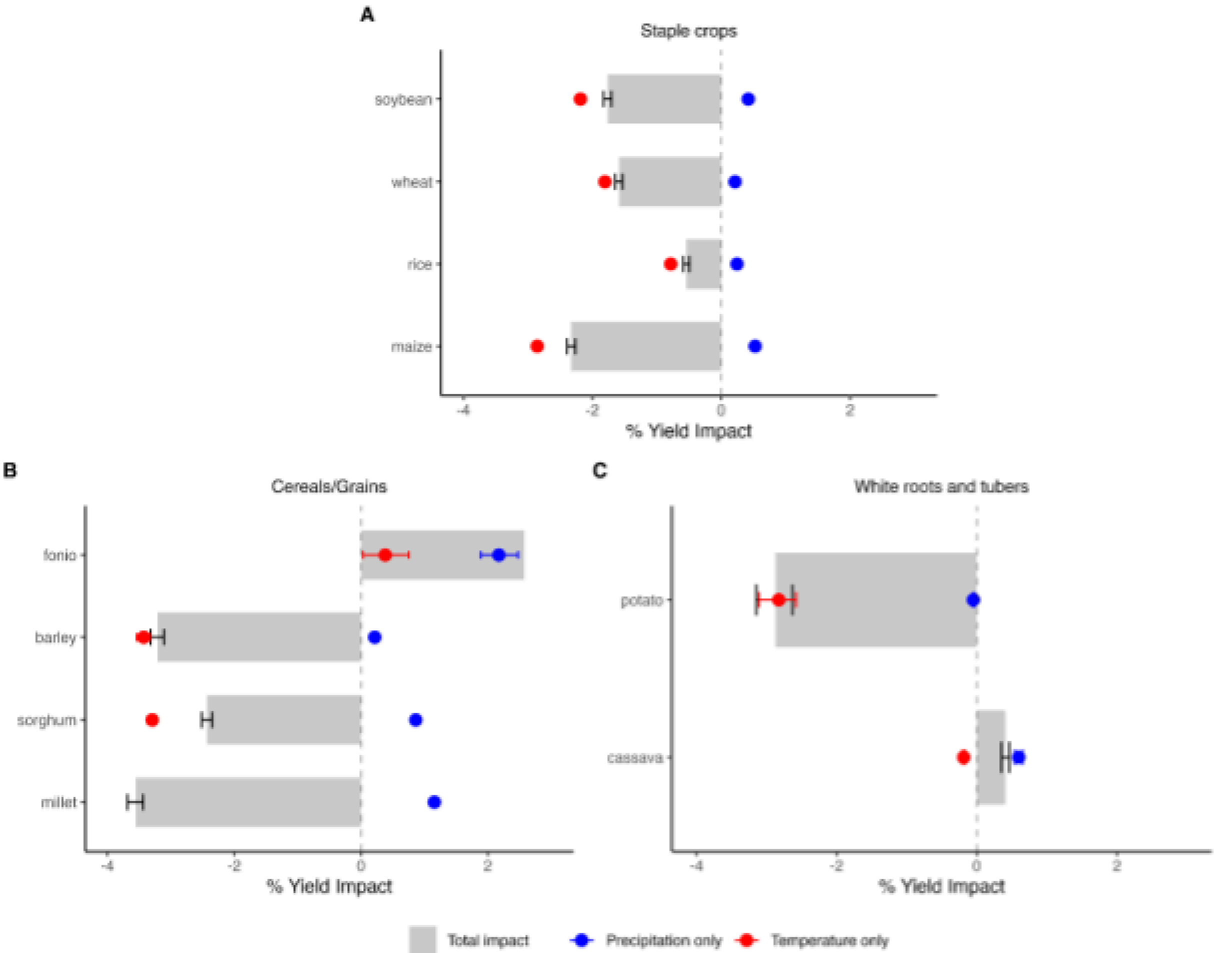


Appendix A Figure 1. Yield Quartile Groups for (A) maize, (B) rice, (C)wheat and (D) soybean.

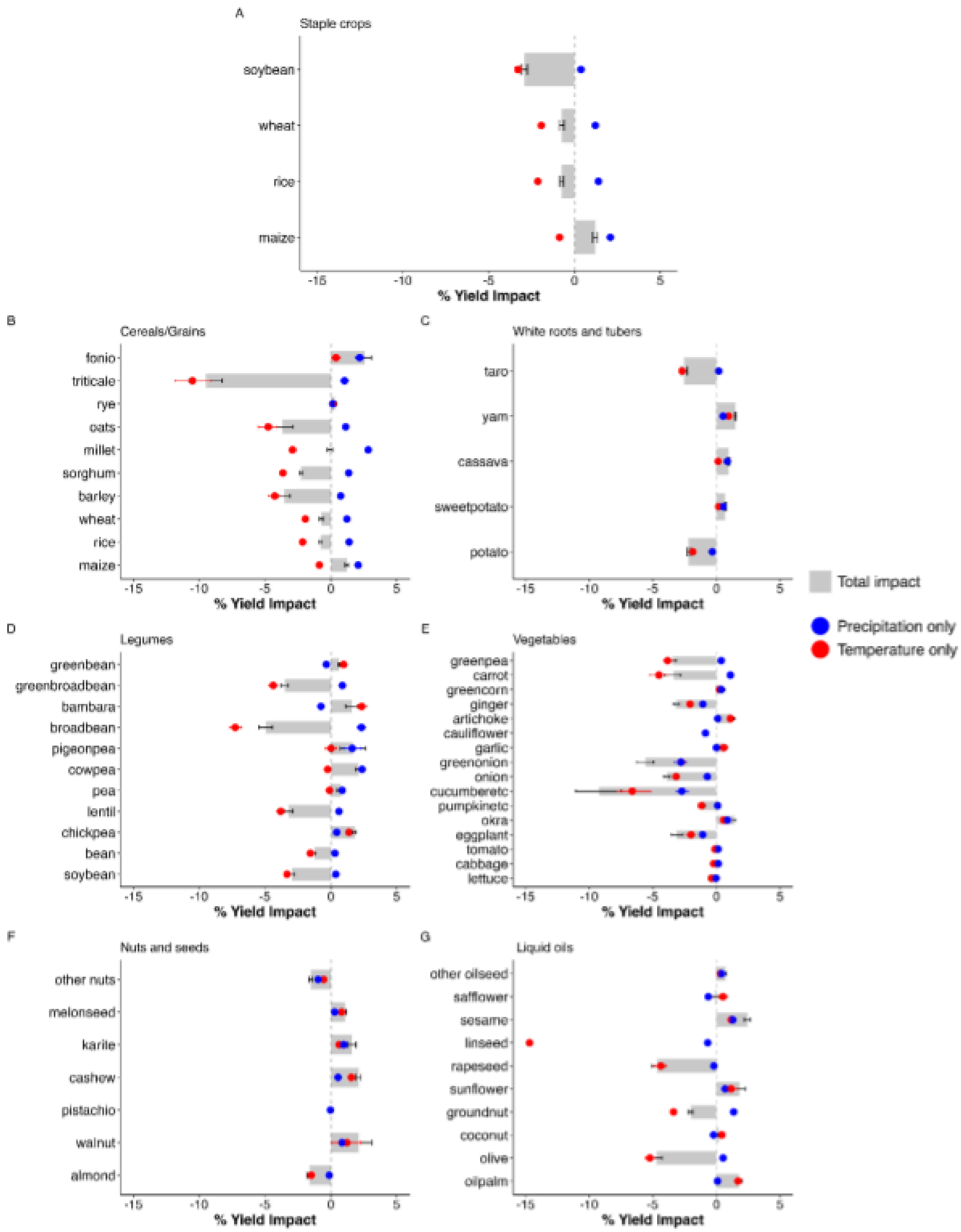
Figure 1(A–D). Each panel displays yield quartile groups by crop, which were used to form country clusters for the panel regressions. Separate regressions were estimated for each group to account for differences in weather conditions and management intensity.

Robustness Checks

As a robustness check, we re-estimate climate impacts using a pooled specification that does not stratify countries by yield quartiles. Instead of estimating separate damage functions for each quartile, this approach pools all observations and estimates a single set of climate response parameters. Results are presented in Figure 2 (global) and Figure 3 (Africa).



Appendix A Figure 2. Global climate impacts on major crops using all countries pooled together.



Appendix A Figure 3. Africa climate impacts on major crops using all countries pooled together.

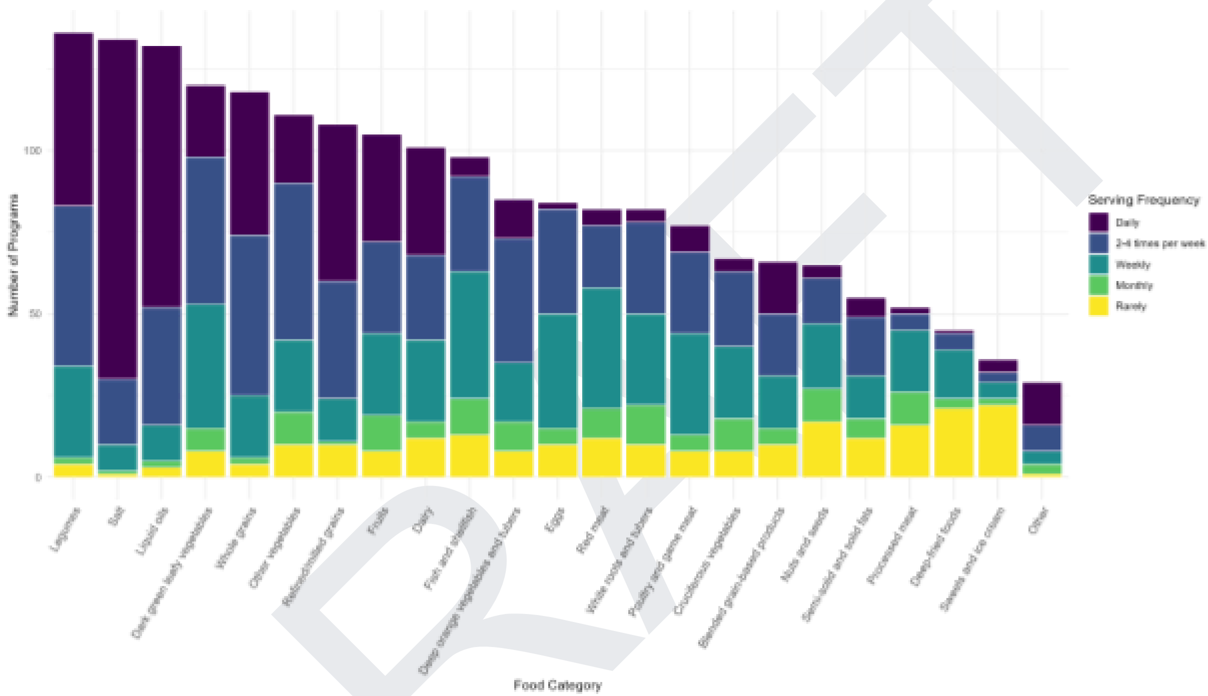
Appendix B: Empirical Methods Details - Climate Impacts on Food Prices

We report simple pairwise correlation between yield and prices for the four main staple crops in Figure 1, within individual countries over time. We observe significant heterogeneity in these correlations, with a wide range of positive and negative values, indicating there are large potential confounders affecting the relationship between yields and prices. To address these confounders, we fit a fixed effect regression model to identify the impact of yields on prices in Figure 20 in the main manuscript.

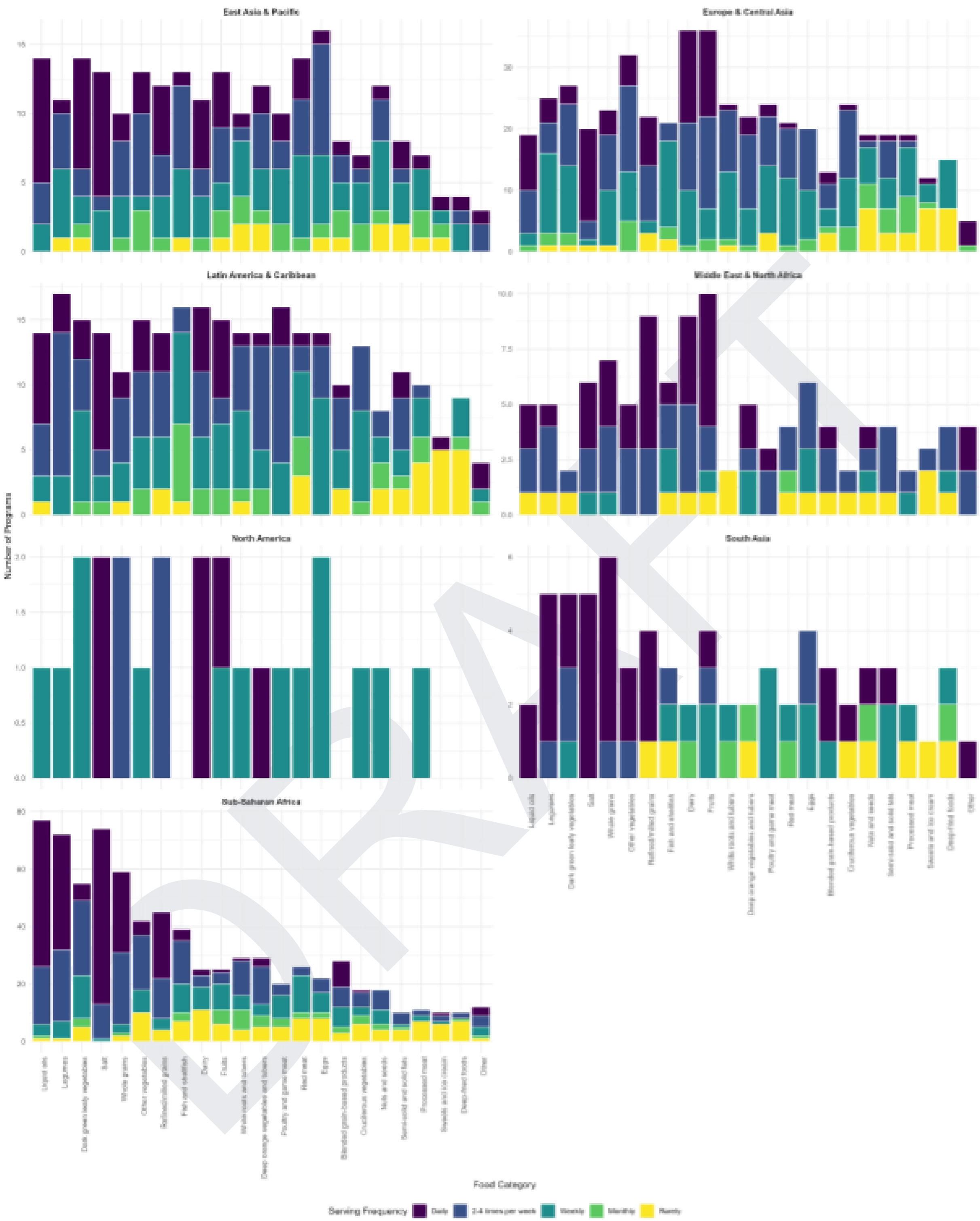
Appendix B Figure 1. Country-wise correlations between annual yields and annual domestic prices over time show substantial heterogeneity that deviates from standard economic expectations.

Appendix C: School Meal Programs and Plate Composition Details

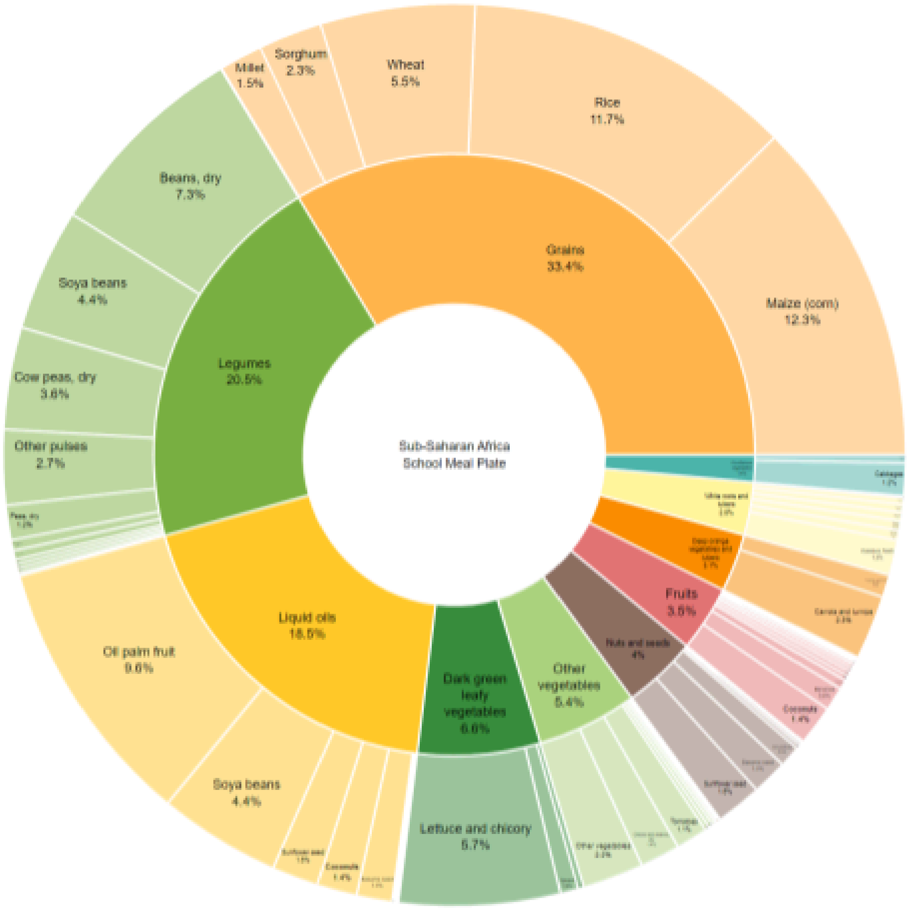
Figures 1 and 2 in this appendix show the number of programs reporting to the GNCF survey and the frequencies they report serving each food group. Figure 1 provides the information globally; with Figure 2 showing the information broken down by region. Figure 3 shows the matching between survey responses and supply utilization accounts information across all African programs.



Appendix C Figure 1. Number of school feeding programs providing food groups by serving frequency, globally.



Appendix C Figure 2. Number of school feeding programs providing food groups by serving frequency, by region.



Appendix C Figure 3. Average plate composition of 85 programs in 40 countries of Sub-Saharan Africa.

Case Studies

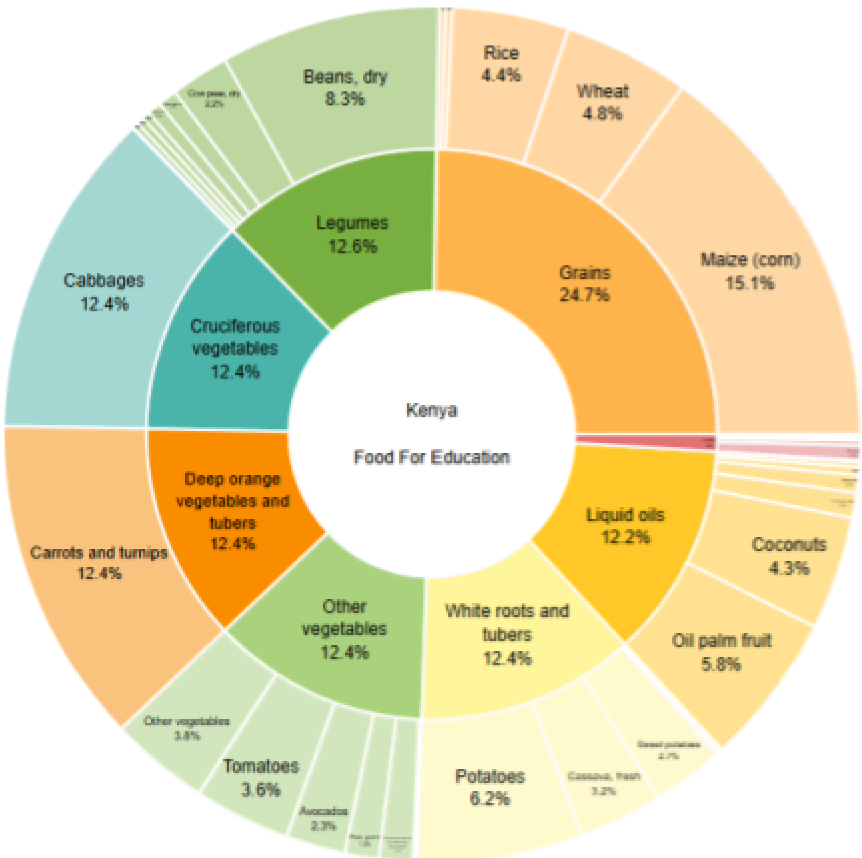
Here we present a more detailed look at four countries (Kenya, Ethiopia, Brazil, and the Philippines) where our team was able to speak directly with program staff. We were able to combine this interview information with survey data to understand the strengths and limitations of our methodology, and also to get a richer picture of how staff think about procurement, limitations on procurement timeframes, and logistical challenges with each program. We summarize some of this information below.

The **Ethiopia Home Grown School Feeding Program** provides meals to about 7 million students. The program reports providing liquid oils daily and cereals (whole grains, blended grain-based products), nuts and seeds, legumes two to four times per week, and salt daily. Liquid oils make up almost half the estimated plate, primarily from sunflower seed (24%) and oil palm fruit (18%); grains make up 32% of the plate, predominantly maize (13%), wheat (10%), and sorghum (6%); legumes make up 15% of the plate, including a wide variety of types of legumes; and nuts and seeds make up about 5% of the plate, predominantly groundnuts (3%) (Figure X).

Appendix C Figure 4. Representative plate of the Ethiopia Home-Grown School Feeding Program using the program's reported food group frequency and FAO Supply Utilization Account data on Ethiopia's crop basket.

Based on expert consultation, school meals within the Ethiopia Home-Grown School Feeding Program are predominantly maize, and some wheat and rice, with a legume and sunflower oil or palm oil, with limited fruit, vegetables, and animal-source foods. Our approximation of an average school meal plate within this program is thus likely a relatively good estimate of the true composition.

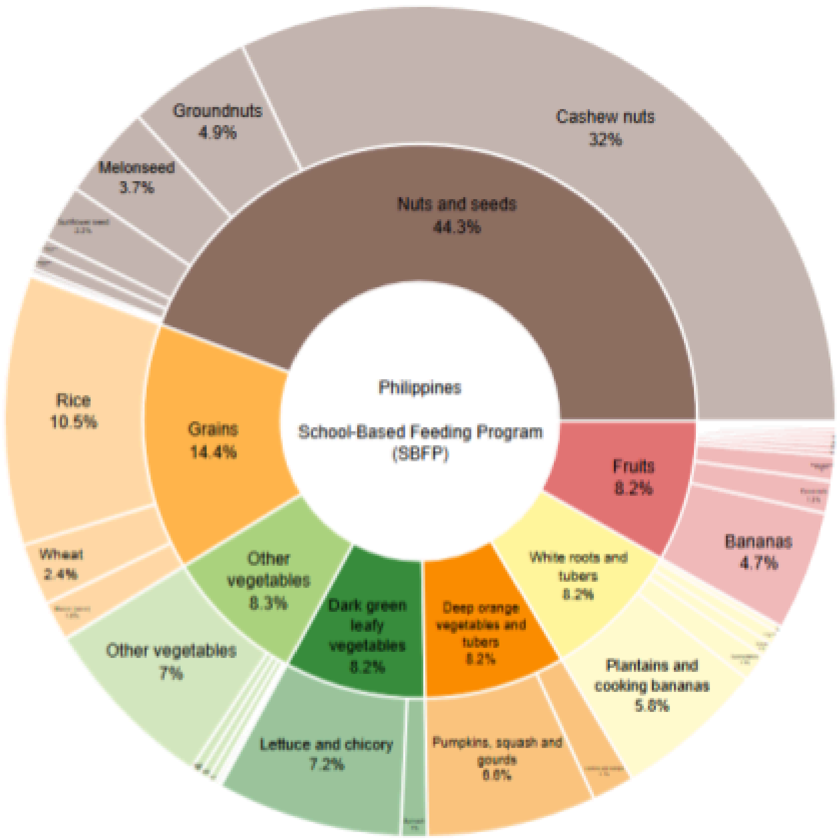
The **Kenya Food for Education Program** provides meals for 1.6 million students and reports providing a diverse food plate including whole grains, refined/milled grains, deep orange vegetables and tubers, cruciferous vegetables, other vegetables, legumes, liquid oils, white roots and tubers, and salt daily, and fruits monthly. We estimate that the representative plate is one-quarter grains, comprising maize (15%), wheat (5%), and rice (4%); and slightly over one-tenth each of legumes, mostly dry beans (8%) and cowpeas (2%); cruciferous vegetables coming from cabbages (12%); deep orange vegetables and tubers coming from carrots (12%); other vegetables including tomatoes (4%), other vegetables (4%), and avocados (2%); white roots and tubers including potatoes (6%), cassava (3%) and sweet potatoes (3%); an liquid oils, predominantly oil palm fruit (6%) and coconut (4%). The plate is 1% fruit, about 0.5% bananas, consistent with the monthly distribution of this food group.



Appendix C Figure 5. Representative plate of the Kenya Food for Education program using the program's reported food group frequency and FAO Supply Utilization Account data on Kenya's crop basket.

Based on expert consultation, the Kenya Food for Education school meals are standardized and 550g, with a specified protein-to-carboydrate ratio (1:1.5). Meals are predominantly rice and legumes (e.g., beans, green gram), with cabbage, carrots, onions, or tomatoes. Fruits like banana are provided every 2 weeks. The program does not serve animal products. In some sites, a maize porridge is served instead of rice. We are thus underestimating rice on the typical school meal plate and overestimating maize and roots/tubers, though the rest of the plate is likely a good approximation of average school meals within the program.

The **Philippines School-Based Feeding Program** serves almost 3.5 million students, with an explicit priority of serving children already suffering from malnutrition. The program reports providing dairy daily, eggs and nuts/seeds two to four times per week, refined/milled grains weekly, and dark green leafy vegetables, deep orange vegetables and tubers, fruits, other vegetables, and white roots and tubers monthly. As our estimation of the representative plate only includes vegetable crops, we do not portray the program's regular provision of dairy and eggs. We estimate that the representative plate for plant-based foods is 44% nuts and seeds, primarily from cashew nuts (32%); 14% grains, primarily rice (11%); and the rest of the plate divided between other vegetables (8%); dark green leafy vegetables, primarily lettuce (7%); deep orange vegetables and tubers, primarily pumpkins, squashes, and gourds (7%); white roots and tubers, primarily plantains and cooking bananas (6%); and fruits, primarily bananas (5%).



Appendix C Figure 6. Representative plate of the Philippines School-Based Feeding Program using the program's reported food group frequency and FAO Supply Utilization Account data on Philippines' crop basket.

The **Brazil National School Feeding Program (Programa Nacional de Alimentação Escolar)** provides meals to 35.8 million students. The program reports providing a wide diversity of foods across almost all food groups, including animal-source foods and plant-based foods. Dairy, eggs, poultry and game meat, processed meat, red meat, and semi-solid and solid fats are served two to four times per week. Blended grain-based products, refined/milled grains, whole grains, cruciferous vegetables, dark green leafy vegetables, deep orange vegetables and tubers, other vegetables, fruits, legumes, liquid oils, nuts and seeds, and white roots and tubers are also served two to four times per week. Fish and shellfish are provided monthly. As with the case study of the Philippines, our estimation of Brazil's representative school meal plate does not include animal-source foods. We estimate that the representative plate for plant-based foods is one-quarter grains, including wheat (10%), maize (7%), and rice (7%); and then a relatively even distribution of liquid oils, primarily from soya beans (4%); fruits including bananas (2%) and coconuts (2%); dark green leafy vegetables including lettuce and chicory (8%); other vegetables including tomatoes (4%), other vegetables (3%), and onions and shallots (2%); white roots and tubers including cassava (4%) and potatoes (4%); legumes including dry beans (4%) and legumes (4%); and nuts and seeds including sunflower seed (2%), sesame seed (1%), and groundnuts (1%).

Appendix C Figure 7. Representative plate of the Brazil National School Feeding Program using the program's reported food group frequency and FAO Supply Utilization Account data on Brazil's crop basket.

Based on our expert consultation, composition of plates is dependent on the region, but typically consists of a basis of rice and beans, though corn is included in the North East and wheat is included as baked goods. Meat is served daily, though some regions serve fish a couple times per week. A diverse variety of legumes, vegetables, seeds, fruits, and tubers are procured on a weekly basis, with at least 30% coming from local farms. Our representative plate likely underestimates rice on the Brazilian school meal plate, and we are likely also constrained in our estimation of the various types of vegetables and legumes that are provided in school meals. Furthermore, Brazil's FAO Supply Utilization Account basket reports 0 per capita consumption of crops included in our estimation of cruciferous vegetables and dark orange vegetables and tubers, thus these are not included in our representative plate.