

Research Article

Limits to Growth in Global Crop Yields: Insights from Data Mining of the FAOSTAT Database from 1961 to 2023

Thorsten Daubenfeld¹, Louisa Lauenstein¹, Diana Carrasco¹

1. Hochschule Fresenius University of Applied Sciences, Idstein, Germany

We conducted a comprehensive data mining analysis of the FAOSTAT database to assess historical trends and current limits in global crop yield development. The study included 157 major crops across 202 countries from 1961 to 2023, focusing on time series of yield (t/ha) and area harvested (ha). Weighted global average yields and annual maximum yields were calculated for each crop and classified into four categories of temporal evolution: never improved, still increasing, stagnating, and decreasing. Over the study period, total crop production rose by a factor of 3.9, primarily driven by a 2.54-fold increase in average yield, with harvested area contributing a smaller share. Analysis revealed that approximately 77% of global production volume remains in the "still increasing" category for average yield, although this share has declined from previous decades. In contrast, only about a quarter of production volume continues to experience increases in maximum yield, suggesting a growing number of crops nearing biophysical yield limits. Yield-area diagrams, categorized by a semi-quantitative "L-chart" approach, indicate that high yields are predominantly restricted to relatively small harvested areas, with over 90% of crops showing strong spatial limitations to yield scalability. These findings imply that opportunities for further global crop production expansion via yield improvement are increasingly constrained, and that recent output gains have largely depended on continued expansion of harvested area.

Correspondence: papers@team.qeios.com — Qeios will forward to the authors

1. Introduction

The continued growth of the global population ^{[1][2]}, rising per-capita meat consumption ^[3], and the increasing demand for energy crops such as bioethanol ^{[2][4]} are intensifying pressure on agricultural systems to produce more food, feed, and energy crops ^[5]. Most of these products are derived from field-grown crops. Against this

backdrop, a central question in agricultural science is whether global crop production can keep pace with future demand [\[6\]\[7\]](#).

Debates regarding limits to food production and their impact on population growth are longstanding [\[8\]\[9\]\[10\]](#) and have gained renewed relevance as forecasts suggest the need to double food production by 2050, despite resource constraints on our finite planet [\[2\]\[11\]\[12\]](#). While projections vary, some analyses already highlight that current yield trends may be insufficient to meet future global needs [\[13\]](#).

Crop production (P , in tonnes) can fundamentally be increased via two pathways: boosting the yield per unit area (Y , in t/ha) or enlarging the harvested area (A , in ha). Their relationship is described by equation 1:

$$\frac{P}{t} = \frac{Y}{t \cdot \text{ha}^{-1}} \cdot \frac{A}{\text{ha}} \quad (1)$$

However, the total available land for crop cultivation is inherently limited, making further expansion of harvested area an unsustainable long-term strategy. Yield improvement thus emerges as the primary avenue for sustainably increasing crop production. Consequently, assessing the potential for future yield gains is of high practical significance to global food security.

To address this issue, we performed a comprehensive analysis of the FAOSTAT crop production database, examining temporal developments in yields (Y) and harvested areas (A) for all 162 primary crops recorded between 1961 and 2023, across all reporting countries. We focus on both the weighted global average yield and annual crop-specific maximum yields, providing a basis for evaluating historical patterns as well as potential future trends.

Interpreting FAOSTAT data at a global scale presents methodological challenges: differences in data reporting practices, timing, and national estimation approaches introduce uncertainty into yield, production volume, and area statistics [\[14\]](#). Nonetheless, FAOSTAT remains the most comprehensive and widely-used source for such cross-country, long-term analyses.

It is important to note that our study relies on the "area harvested" variable, as global data on "cultivated area" are not available. "Area harvested" serves as the most practical and consistent metric for large-scale comparisons, although multiple harvests per year and other reporting nuances may introduce further data constraints.

Drawing on concepts from systems theory and ecology, we hypothesize that crop yield trajectories generally follow limited growth patterns such as S-shaped curves – possibly with overshoot and subsequent stagnation or decline – reflecting broader biophysical dynamics [\[10\]\[15\]\[16\]\[17\]\[18\]\[19\]\[20\]](#). Empirical studies support the existence of this type of yield evolution for various crops [\[6\]\[21\]\[22\]](#), and there are indications that crop yield projections may be overly optimistic when compared to realized trends [\[23\]](#).

While individual crop modeling and regional scenario analyses have been conducted [22], a systematic and quantitative overview encompassing all global crops has, to date, been lacking. The present study aims to fill this gap by providing a high-level assessment of yield and harvested area trends, setting the stage for future research and evidence-based decision-making in the context of looming resource constraints.

2. Materials and methods

2.1. Data Acquisition and Processing

All underlying data were retrieved from the FAOSTAT online database (<https://www.fao.org/faostat/en/#data/QCL>) on March 12, 2025, including records for area harvested, yield, and crop production quantity for all primary crops. Data processing was conducted in R (version 4.4.2) using RStudio (2024.12.1) on Intel Mac OS X 10_15_7.

From the original set of 162 primary crops, four were excluded due to missing values for either yield or harvested area, and a fifth crop was omitted due to restricted temporal coverage – only one year of data – which precluded any analysis of yield trends. The excluded crops were: “Balata, gutta-percha, guayule, chicle and similar natural gums in primary forms or in plates, sheets or strip”, “Brazil nuts, in shell”, “Cassava leaves”, “Cair, raw”, and “Mushrooms and truffles”. These five crops together represented a cumulative production volume of 99 million tonnes in 2023, accounting for approximately 1.0% of global crop production. Consequently, the final study set comprises 157 crops with sufficient data quality and temporal coverage.

2.2. Calculation of Weighted Global Average Yields

For each crop and year within the dataset, both yield (Y , in t/ha) and harvested area (A , in ha) were compiled at the country level. The weighted global average yield for each crop and year was computed using equation 2:

$$\text{weighted yield} = \frac{Y_i \cdot A_i}{\sum_i A_i} \quad (2)$$

Where Y_i denotes the yield of country i and A_i its corresponding harvested area in the examined year. This approach ensures that each country's yield contributes to the global average in proportion to its share of the harvested area.

For visualization, annual country-level yields and calculated global weighted averages were plotted over the time period 1961-2023 for each crop. This facilitated year-by-year comparative inspection of global yield and its variability.

The temporal evolution of both weighted average yields and annual top yields (see below) was classified according to four categories: (1) yields never improved, (2) yields still increasing, (3) yields stagnating, and (4)

yields decreasing (Fig. 1, bottom). Description of the classes was based on the study by Ray et al. [6]. The category “Yields collapsed” was changed to “Yields decreasing”, reflecting the fact that a decrease in yield does not always correspond to a collapse of the yield.

Classification decision logic followed a specified algorithm (Fig. 1, top), wherein a compound annual growth rate (CAGR) of 0.3% was used to distinguish “still increasing” yields (equivalent to a minimum of 20% yield gain over the analysis period), and a decline by $\geq 20\%$ was designated as “decreasing.” Intermediate cases were evaluated for stagnation.

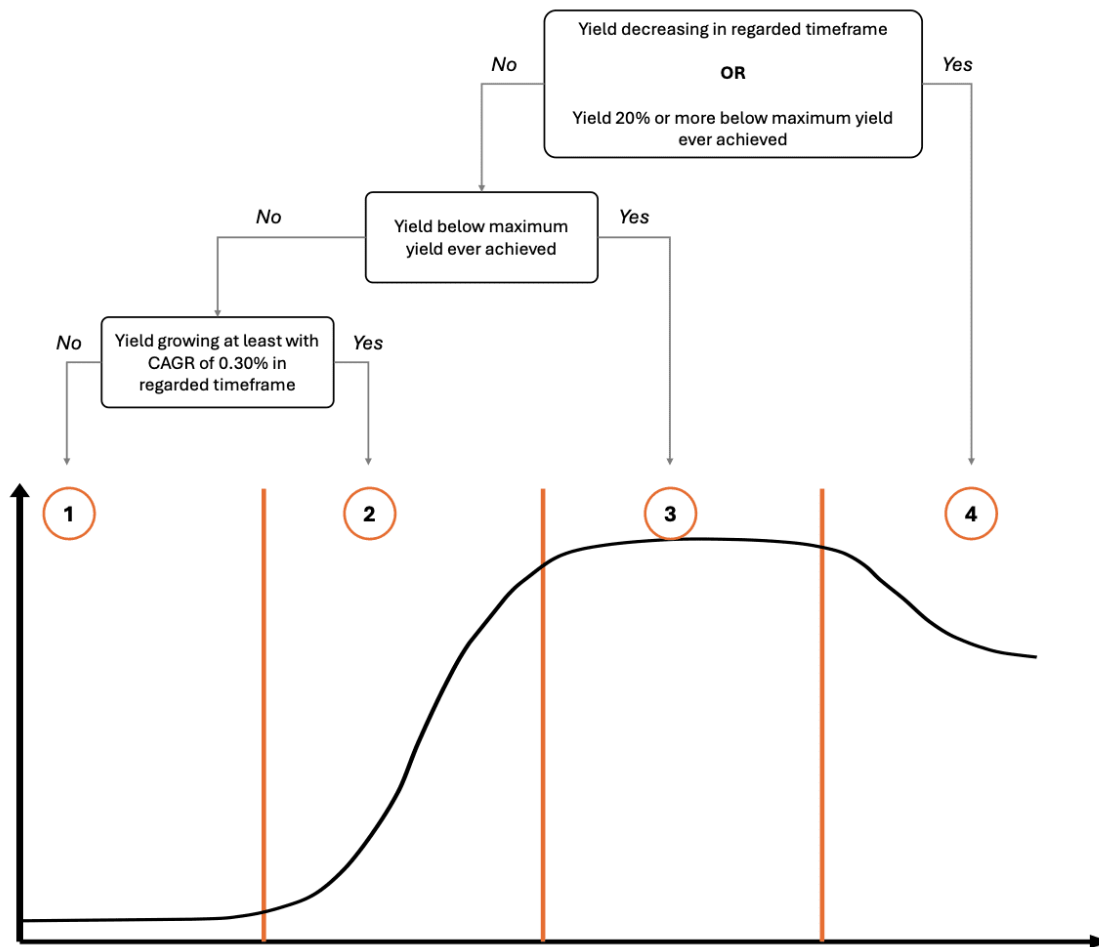


Figure 1. Top: Decision tree for categorizing weighted average yield and maximum yield trends into four distinct categories. For a detailed methodological description, see main text. Classification scheme for the temporal evolution of weighted average yield and maximum (top 5) yield. Bottom: Categories: (1) yields never improved; (2) yields still increasing; (3) yields stagnating; (4) yields decreasing.

Analyses were performed for the years 1980, 2000, and 2023 to capture temporal shifts in yield development categories. Given the underlying uncertainties and inconsistencies in reporting, analyzing further time points would create a misleading impression of statistical precision.

2.3. Analysis of Maximum Yields ("Top 5" Approach)

To independently assess trends in maximum yield, we identified the five highest country-level yields ("top 5") per crop and year throughout 1961-2023. These values were extracted irrespective of country and modeled with a trend line using LOESS (Locally Estimated Scatterplot Smoothing) as implemented via the `geom_smooth` function in the `ggplot2` package for R (method = "loess", span = 0.3) [24][25]. LOESS is a non-parametric regression technique that fits low-degree polynomials to local subsets of the data, with points weighted according to proximity to each target value. The selected span parameter (0.3) balances the need for sensitivity to local changes versus suppressing noise, capturing fine-scale temporal patterns in maximum yield development.

Maximum yields for each crop were subsequently assigned to one of the four temporal categories, using the same decision tree classification as for global averages (Fig. 1).

2.4. Assessment of Yield Scalability via Yield-Area Diagrams ("L-Chart" Classification)

To investigate the relationship between yield and the scale of crop cultivation, we created scatterplots for each crop species, mapping individual country-year data points (yield vs. area harvested) over the entire study period (1961-2023). These visualizations were generated in RStudio and Microsoft Excel.

For systematic analysis, each plot was divided into a 5×5 grid of equally sized rectangles. The distribution of data points was evaluated to identify which grid sectors contained the datapoints nearest to the upper right corner (large area harvested and high yield). Diagrams with data largely confined to the left column and lower row were classified as "type 1 L-charts", indicating high yields restricted to small areas. Diagrams with more extensive spread into adjacent rows/columns were assigned to higher types (e.g., "type 2 L-chart", etc.), reflecting increasing scalability.

For visual support, a color gradient from red (low yield/small area) to green (high yield/large area) was used (see Fig. 12). Full details of this procedure and representative examples are provided in Fig. 12. The subjective nature of this approach is acknowledged; nonetheless, it enables a semi-quantitative assessment of yield scalability across a diverse set of crops.

Aggregated results from the L-chart classification (across all 157 crops) are presented as both the share of crop count and production volume per type.

3. Results

3.1. Contribution of Yield and Harvested Area to Crop Production, 1961-2023

Analysis of global crop production across 157 major crops reveals a marked increase in output since 1961. Total production rose from 2.54 Gt in 1961 to 9.88 Gt in 2023 (Fig. 2), representing a 3.90-fold increase and a compound annual growth rate (CAGR) of 2.2%. During this period, yield improved from 2.61 t/ha to 6.64 t/ha, a 2.54-fold increase (CAGR 1.5%), while harvested area expanded by a factor of 1.53 (CAGR 0.7%).

These values indicate that yield improvements contributed approximately two-thirds of the growth in production quantity over the study period, whereas expansion of harvested area accounted for the remaining third. Given the natural constraints on land availability, further gains in harvested area are inherently unsustainable, reinforcing the need to focus on yield development for future crop production increases.

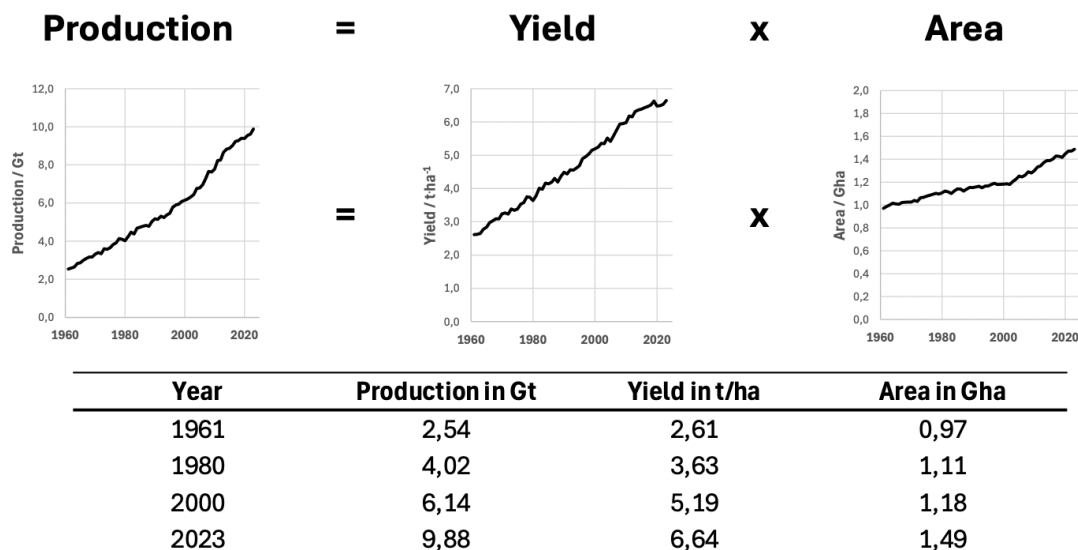


Figure 2. Trends in production quantity, yield, and harvested area for all 162 crops in the FAOSTAT database at the global scale from 1961 to 2023.

Examination of temporal trends (Fig. 2) shows that average yield followed an almost linear increase from 1961 onward. In contrast, harvested area displayed a more pronounced rise in recent decades. This suggests that, although yield remained the primary driver of production growth over the long term, increases in harvested area have become more significant to overall output, particularly in the last 20 years.

Further investigation into the underlying drivers of these trends is beyond the scope of this data-focused analysis and will be considered in subsequent chapters.

3.2. Evolution of Weighted Global Average Crop Yield

The temporal evolution of weighted global average yield was evaluated for all 157 crops included in the analysis, covering the period from 1961 to 2023. For each crop, annual yield and harvested area were aggregated at the country level, and the weighted global average yield was calculated as outlined in the Methods section (equation 2).

Figure 3 displays an example of the time series for wheat, showing both country-level yields and the calculated weighted global average yield per year. This visualization allows for a direct comparison between global trend and national variability across the entire time span. The results for wheat demonstrate that the weighted average yield has increased in an almost linear manner throughout the period 1961-2023. In contrast, the maximum observed yield has remained relatively stable at around 10 t/ha and has not shown further increase over the past two decades.

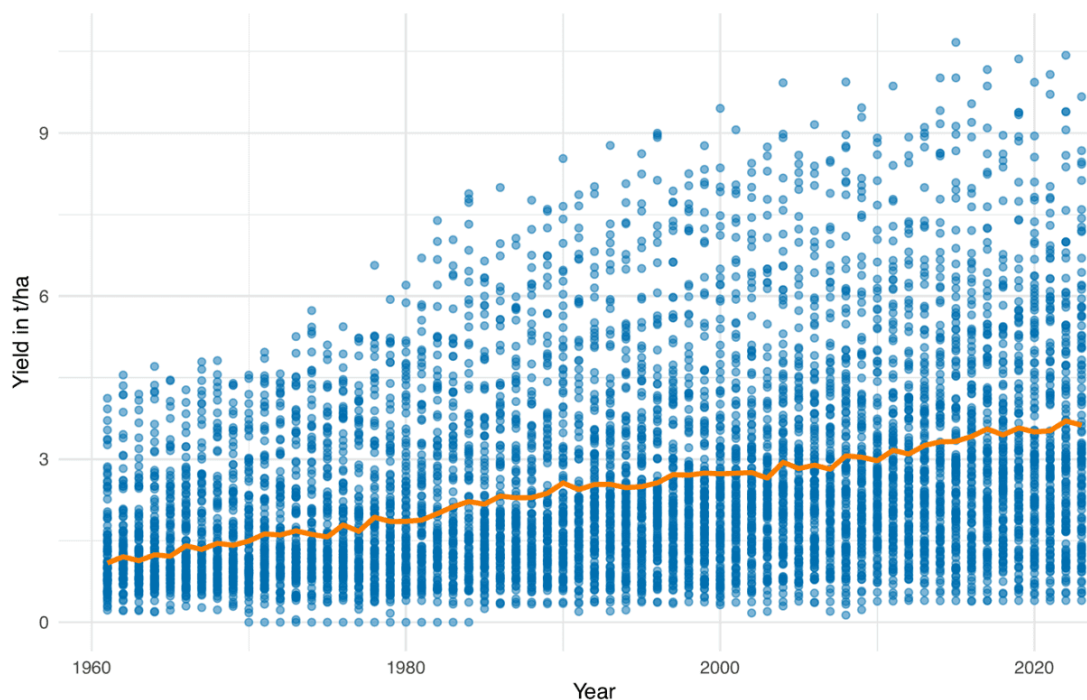


Figure 3. Temporal evolution of wheat yield (t/ha) from 1961 to 2023. Individual country-year yields are shown in blue shades for visual clarity; the orange line indicates the weighted global average yield for each year.

To summarize yield development, each crop's trajectory was assigned to one of four categories: never improved, still increasing, stagnating, or decreasing, as defined and classified by the decision tree in Fig. 1. Selected examples of these classification outcomes are presented in Fig. 4, with the full results documented in Table 1.

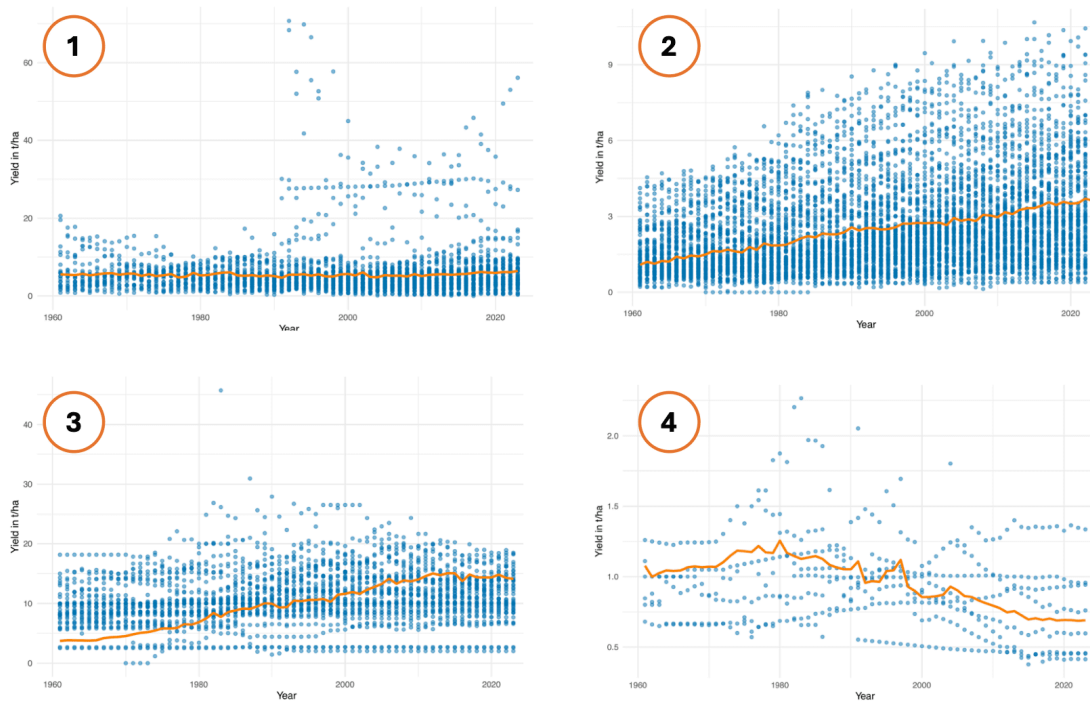


Figure 4. Selected examples illustrating the classification of crops based on the temporal evolution of weighted average yield: (1) cherries: yields never improved; (2) wheat: yields still increasing; (3) oil palm fruit: yields stagnating; (4) agave fibres: yields decreasing.

Category	1		2		3		4	
	Yields never improved		Yields still increasing		Yields stagnating		Yields decreasing	
Number of crops	12 (6%)		91 (56%)		32 (20%)		22 (14%)	
Share of production volume 2023	0.6%		76.7%		21.3%		1.3%	
Crops	Cherries, Currants, Other berries and fruits of the genus <i>vacinium</i> , Other pome fruits, Other pulses, Other stimulant spice and aromatic crops, Other tropical fruits, Pigeon peas (dry), Poppy seed, Quinoa, Sals (raw), Triticale		Almonds (in shell), Anise / fadian / coriander / cumin / caraway / fennel and juniper berries (raw), Apples, Apricots, Avocado, Avocado, Avocado, Bananas, Barley, Beans (dry), Blueberries, Broad beans and horse beans (dry), Broad beans and horse beans (green), Cabbages, Canary seed, Cantaloupes and other melons, Carrots and turnips, Cashew nuts in shell, Castor oil seeds, Cauliflowers and broccoli, Cereals, Chick peas (dry), Chillies and peppers (dry, raw), Chillies and peppers (green), Coconut in shell, Coffee (green), Cow peas (dry), Cranberries, Cucumbers and gherkins, Dates, Edible roots and tubers with high starch or mulin content (fresh), Eggplants (aubergines), Figs, Ginger (raw), Grapes, Groundnuts (excluding shelled Hazelnuts) in shell, Hop cones, Jute (raw or retted), Kapok fruit, Kenaf and other textile bast fibres (raw or retted), Leeks and other alliacious vegetables, Lemons and limes, Lettuce and chicory, Linseed, Locust beans (carrots), Lupine, Maize (corn), Mangoes / guavas and mangosteens, Maté leaves, Millet, Mixed grain, Mustard seed, Nutmeg / mace / cardamoms (raw), Oats, Onions and shallots (dry, excluding dehydrated), Onions and shallots (green), Other fibre crops (raw), Other fruits, Other oil seeds, Peaches and nectarines, Pears, Peas (green), Pepper (raw), Pineapples, Plantains and cooking bananas, Potatoes, Pumpkins / squash and gourds, Quinces, Ramlie (raw or retted), Rape or colza seed, Raspberries, Rice, Rye, Softflower seed, Seed cotton (unspinned), Sesame seed, Sorghum, Sour cherries, Spinach, Strawberries, String beans, Sugar beet, Sugar cane, Tangerines / mandarins / clementines, True hemp (raw or retted), Unmanufactured tobacco, Vetches, Walnuts in shell, Watermelons, Wheat		Asparagus, Buckwheat, Cassava (fresh), Chestnuts in shell, Cocoa beans, Green corn (maize), Green garlic, Hempseed, Nut fruit, Lentils (dry), Nut at rubber in primary forms, Oil palm fruit, Olives, Oranges, Other beans (green), Other citrus fruit, Other stone fruits, Other sugar crops, Other vegetables (fresh), Papayas, Peas (dry), Peppermint / spearmint, Pistachios in shell, Pineapples and grapefruits, Soy beans, Sunflower seed, Sweet potatoes, Taro, Tea leaves, Tomatoes, Tung nuts, Yautia		Albaca / marilla hemp (raw), Agave fibres (raw), Bambara beans (dry), Castanewapple, Chicory roots, Cinnamon and cinnamon-tree flowers (raw), Cloves (whole stems, raw), Fux (raw or retted), Fonio, Gooseberries, Jobba seeds, Kante nuts (beans), Kola nuts, Melonseed, Ora, Other nuts (excluding wild edible nuts and groundnuts) in shell, Perseemons, Pums and sloes, Pyrethrum (dried flowers), Tallowtree seeds, Vanilla (raw), Yams	

Table 1. Classification results for the temporal evolution of weighted average yield of 157 crops in 2023.

A detailed visualization of the evolution of weighted average crop yield for all 157 crops analyzed can be found in the supplementary material.

Out of the 157 crops analyzed, approximately 60% currently exhibit increasing average yields. These crops represent roughly 77% of global crop production volume, indicating that the weighted global average yield for the majority of production is still on an upward trajectory.

The temporal dynamics of these categories were further assessed for the years 1980, 2000, and 2023 (Fig. 5). The analysis demonstrates a decrease in the proportion of crop production volume assigned to "yields still increasing," falling from 96% in 1980 to 77% in 2023. This shift suggests a gradual change in the distribution of yield development patterns among the major crops over recent decades.

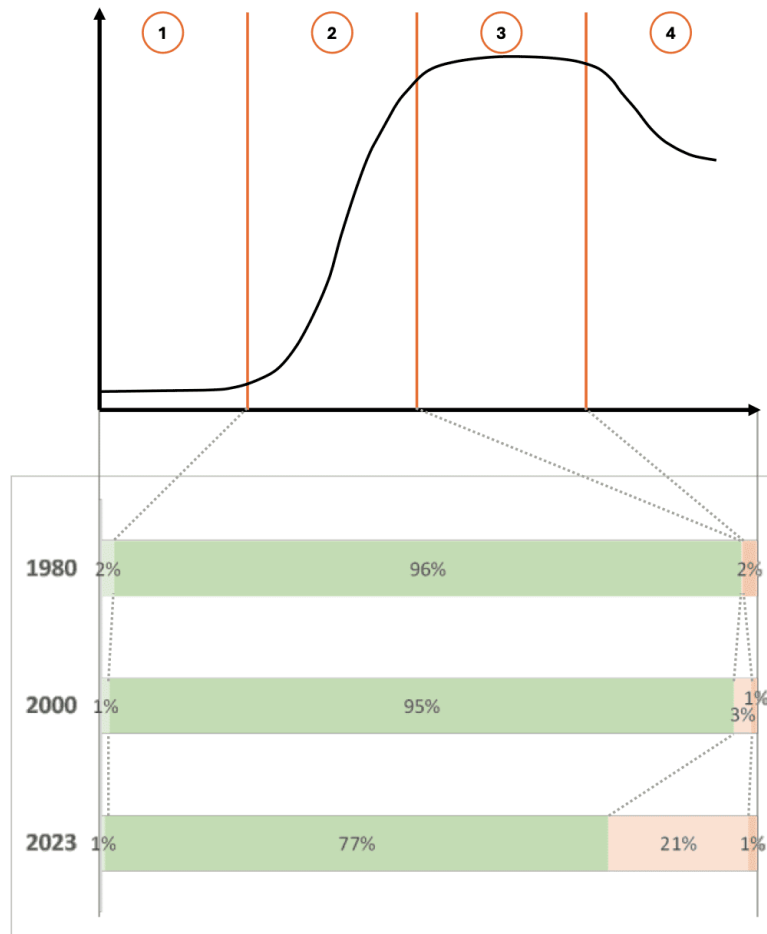


Figure 5. Percentage share of global production volume by category of weighted average yield evolution for the years 1980, 2000, and 2023.

Despite this decrease, the single largest share of global production volume still remains within the "yields still increasing" category as of 2023. On the basis of aggregated data alone, there is no immediate indication that the global weighted average yield is approaching a firm upper limit, although a declining trend in the share of crops with sustained yield growth can be observed.

3.3. Evolution of Maximum Crop Yield

The evolution of annual maximum crop yields was assessed for all 157 crops over the period 1961-2023. For each year and crop, the five highest country-level yields were identified and used to characterize the maximum yield trends. These values were fitted with a LOESS curve, as described in the Methods section, to visualize the underlying temporal trajectory.

Fig. 6 illustrates the case of wheat. While the maximum yield increased steadily from 1961 until approximately 1990, reaching around 10 t/ha, this value has remained largely unchanged since then, with the curve flattening over the last two decades. In recent years, the maximum yield has shown little to no further increase, and a slight decrease is observed.

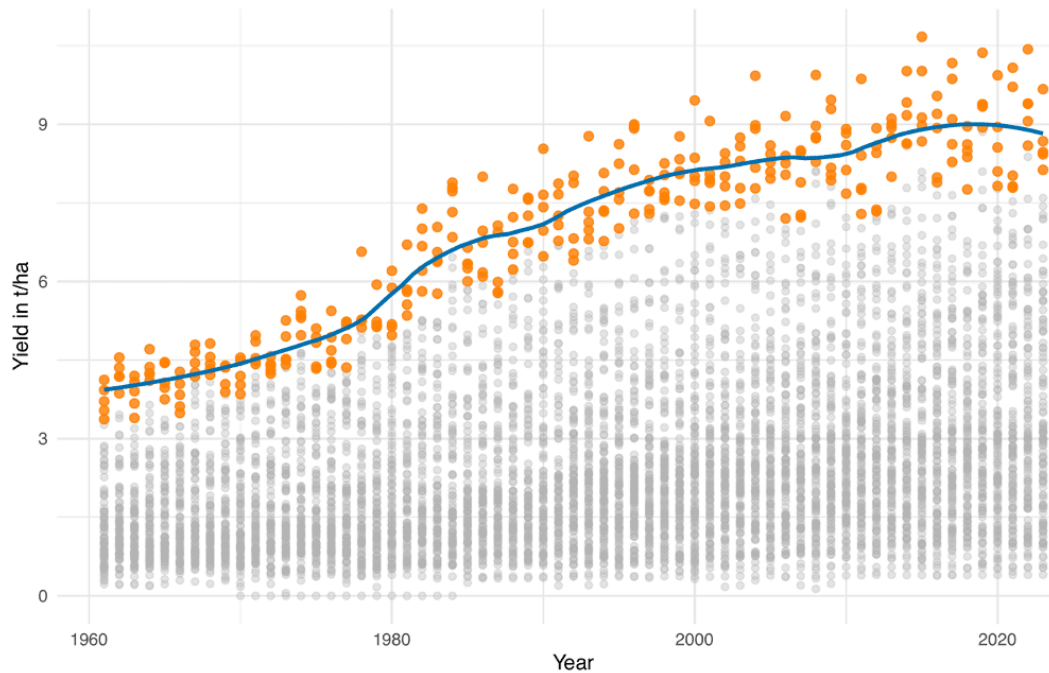


Figure 6. Temporal evolution of wheat yield (t/ha) from 1961 to 2023. Individual country-year yields are shown in shades of gray for visual clarity. Orange dots indicate the top five yields per year, and the blue line represents the LOESS-smoothed trend of the arithmetic mean of these top five yields.

The temporal development of wheat corresponds to the “Yields stagnating” category, as illustrated in Fig. 1.

A detailed visualization of the evolution of maximum crop yield for all 157 crops analyzed can be found in the supplementary material.

To provide an overview, the maximum yield trend for each crop was classified into one of four categories: never improved, still increasing, stagnating, or decreasing (see Fig. 7 for selected examples and Tab. 2 for the full classification).

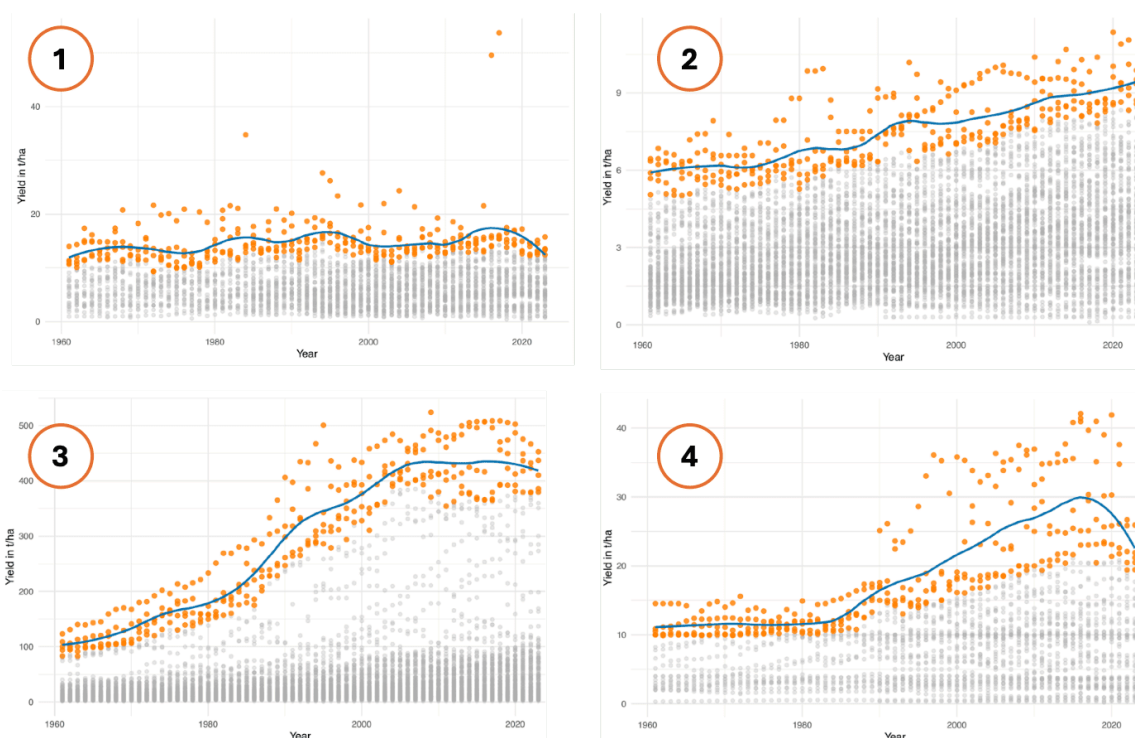


Figure 7. Selected examples illustrating the classification of crops based on the temporal evolution of maximum yield: (1) apricots: yields never improved; (2) rice: yields still increasing; (3) tomatoes: yields stagnating; (4) green corn (maize): yields decreasing.

Category	1 Yields never improved	2 Yields still increasing	3 Yields stagnating	4 Yields decreasing
Number of crops	2 (1%)	64 (41%)	59 (38%)	32 (20%)
Share of production volume 2023	0.1%	26.8%	51.5%	21.7%
Crops	Apricots, Cashewapple	Apricots, Cashewapple, Anise / badian / coriander / cumin / caraway / fennel and juniper berries (raw), Artichokes, Avocados, Barley, Beans (dry), Blueberries, Canary seed, Carrots and turnips, Cassava (fresh), Castor oil seeds, Cereals, Chick peas (dry), Chillies and peppers (dry, raw), Coconuts in shell, Cow peas (dry), Edible roots and tubers with high starch or inulin content (fresh), Grapes, Green garlic, Groundnuts (excluding shells), Hazelnuts in shell, Hempseed, Hop cones, Kiwi fruit, Lemons and limes, Lettuce and chicory, Mangoes / guavas and mangosteens, Melonseed, Millet, Mustard seed, Nutmeg / mace / cardamoms (raw), Okra, Olives, Oranges, Other berries and fruits of the genus vaccinium, Other citrus fruit, Other oil seeds, Other pome fruits, Other pulses, Other stimulant / spice and aromatic crops, Other stone fruits, Papayas, Pepper (raw), Persimmons, Pigeon peas (dry), Pineapples, Plantains and cooking bananas, Pomeios and grapefruits, Pumpkins / squash and gourds, Rammie (raw or retted), Rape or colza seed, Rice, Seed cotton (unginned), Sorghum, Sour cherries, Strawberries, String beans, Sweet potatoes, Taro, True hemp (raw or retted), Unmanufactured tobacco, Vetches, Watermelons, Yams, Yautia	Almonds in shell, Apples, Asparagus, Bambara beans (dry), Bananas, Broad beans and horse beans (dry), Broad beans and horse beans (green), Cabbages, Cashew nuts in shell, Chillies and peppers (green), Cinnamon and cinnamon-tree flowers (raw), Cloves (whole stems, raw), Cocoa beans, Coffee (green), Cucumbers and gherkins, Currants, Dates, Eggplants (aubergines), Figs, Fonio, Ginger (raw), Gooseberries, Jute (raw or retted), Kapok fruit, Lentils (dry), Linseed, Maize (corn), Mixed grain, Natural rubber in primary forms, Oats, Oil palm fruit, Onions and shallots (dry, excluding dehydrated), Onions and shallots (green), Other beans (green), Other fruits, Other nuts (excluding wild edible nuts and groundnuts) in shell, Other tropical fruits, Other vegetables (fresh), Peaches and nectarines, Peas (dry), Peppermint / spearmint, Pistachios in shell, Potatoes, Quinoa, Raspberries, Rye, Sesame seed, Sisal (raw), Soya beans, Spinach, Sugar beet, Sunflower seed, Tangerines / mandarins / clementines, Tea leaves, Tomatoes, Triticale, Tung nuts, Vanilla (raw), Wheat	Abaca /manila hemp (raw), Agave fibres (raw), Areca nuts, Buckwheat, Cantaloupes and other melons, Cauliflowers and broccoli, Cherries, Chestnuts in shell, Chicory roots, Cranberries, Flax (raw or retted), Green corn (maize), Jojoba seeds, Karite nuts (sheanuts), Kenaf and other textile bast fibres (raw or retted), Kola nuts, Leeks and other alliaceous vegetables, Locust beans (carobs), Lupins, Maté leaves, Other fibre crops (raw), Other sugar crops, Pears, Peas (green), Plums and sloes, Poppy seed, Pyrethrum (dried flowers), Quinces, Safflower seed, Sugar cane, Tallowtree seeds, Walnuts in shell

Table 2. Classification results for the temporal evolution of maximum yield of 157 crops in 2023.

Out of the 157 crops analyzed, 64 (41%) were categorized as "still increasing" with respect to their maximum yield, while the remaining crops showed stagnating or decreasing patterns.

Out of the 157 crops analyzed, 64 (41%) were categorized as "still increasing" with respect to their maximum yield, while the remaining crops showed stagnating or decreasing patterns.

However, crops within the "still increasing" category represent only about a quarter of total global crop production volume. The majority – approximately three quarters of global production volume – now falls into categories where maximum yields have plateaued or declined.

The temporal progression of these categories was further examined for the years 1980, 2000, and 2023 (Fig. 8).

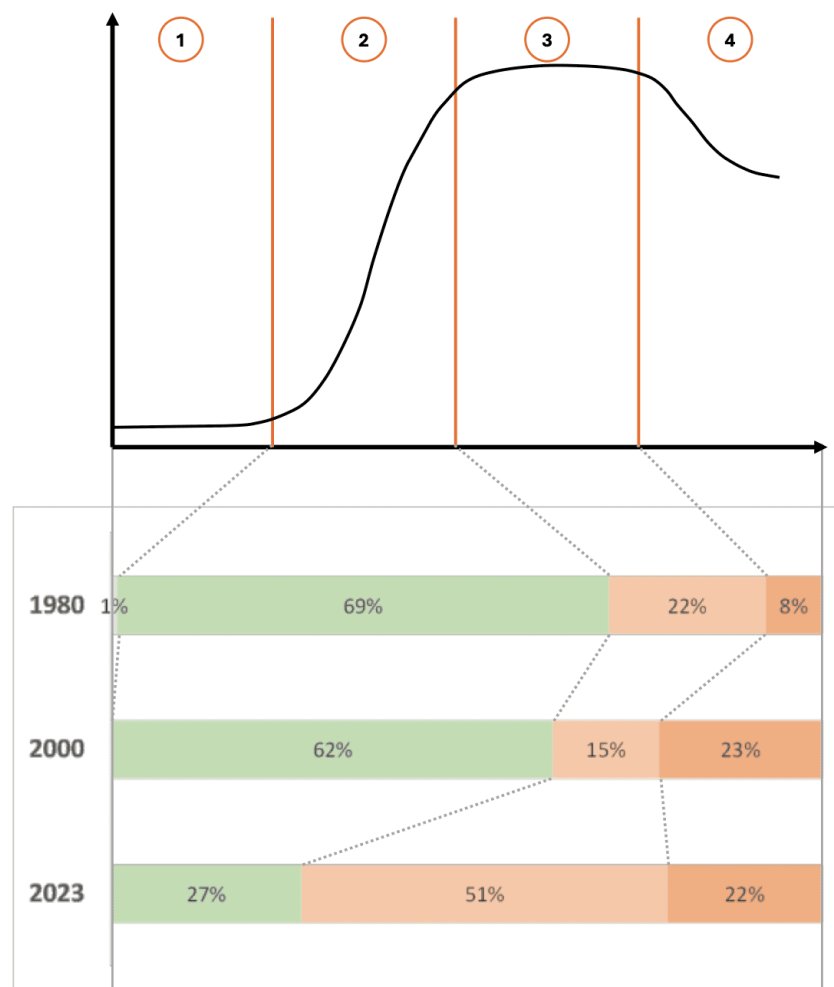


Figure 8. Percentage share of global production volume by category of maximum yield evolution for the years 1980, 2000, and 2023.

Here, the share of crop production volume with still increasing maximum yields has dropped markedly over the last four decades, from 69% in 1980 to just 27% in 2023. This trend indicates that an increasing proportion of crop production is now characterized by limited or declining maximum yield potential.

These results suggest that many crops are approaching their biophysical yield limits at the global scale ^{[26][27]}, with implications for the potential to further increase maximum yields in coming years.

3.4. Comparison of evolution of weighted global average crop yield and maximum crop yield

The comparison between the temporal dynamics of weighted global average crop yields and maximum crop yields provides additional insight into patterns of yield development among the 157 crops included in this

analysis. While both metrics have generally increased over the study period, their trajectories and rates of change differ significantly.

As shown in 3.3, the weighted global average yield for most crops continues to increase, with approximately 77% of global crop production volume in 2023 falling into the "still increasing" category (see Tab. 1 and Fig. 5). In contrast, only about 27% of global production volume exhibits a pattern of increasing maximum yields, with the majority of crops now categorized as stagnating or declining in terms of their highest observed yields (Tab. 2, Figure 8). For wheat, a representative example (Fig. 3 and Fig. 6), the weighted average yield shows a steady, nearly linear rise, whereas the maximum yield has plateaued over the last two decades. This divergence between the trends at the "average" and "maximum" yield levels is evident for many crops.

The categorical analysis (Fig. 9) further highlights this contrast: among the four development categories (never improved, still increasing, stagnating, decreasing), most crops remain in the "still increasing" group when considering the weighted global average yield, but shift towards "stagnating" or "decreasing" when maximum yield is examined.

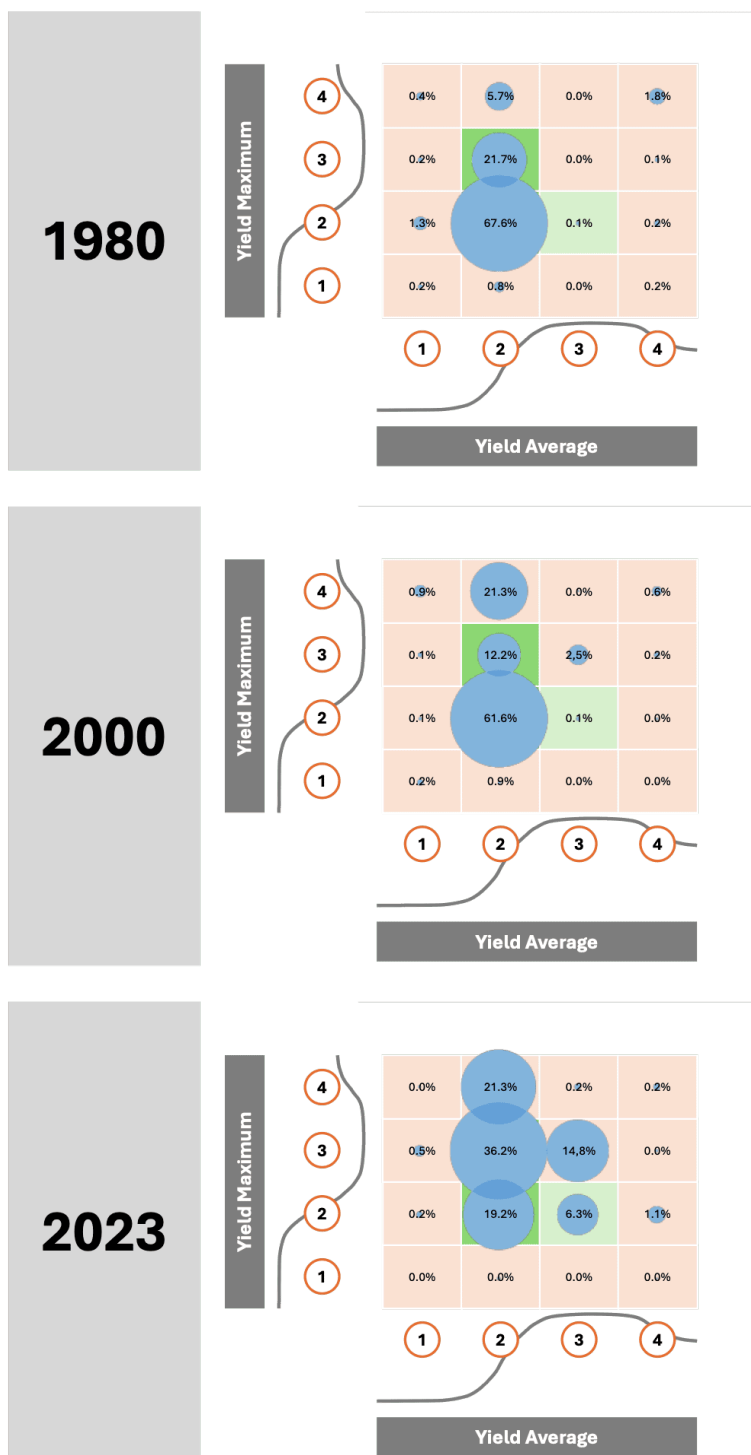


Figure 9. Share of global crop production volume (blue circles) by category according to maximum yield evolution (ordinate) and weighted average yield evolution (abscissa) for the years 1980 (top), 2000 (middle), and 2023 (bottom). Dark green highlights the share of production volume where both weighted average yield and maximum yield are still increasing, or where weighted average yield is still increasing despite stagnating

maximum yield. Light green indicates the share where weighted average yield is stagnating but maximum yield is still increasing.

These findings indicate that while improvements in agronomic practices and technologies have continued to raise average yields across broader cultivation areas, the upper boundary of yield achievement for many crops has remained relatively constant or has even declined in recent years. The disparity between these two metrics suggests limitations in transferring the highest yields observed in specific locations to large-scale, global production.

This comparison supports the interpretation that a growing number of crops are approaching biophysical or system-level yield constraints, with implications for future strategies aimed at increasing overall crop production.

3.5. Relationship Between Crop Yield and Harvesting Area

To assess the relationship between crop yield and harvesting area, we evaluated the distribution of yield and area for each of the 157 crops using the L-chart approach described in the Methods section. For each crop, country-level data for yield and harvested area from 1961 to 2023 were plotted and assigned to a categorical framework designed to characterize the scalability of yield across different cultivation scales.

For illustration, wheat (see Fig. 10) serves as a representative example throughout the study due to its relevance for global food security and diversity of cultivation practices. Wheat demonstrates the ability to achieve relatively high yields across large harvested areas. This pattern is reflected by its assignment to a higher chart type (“L chart type 2”), indicating that, for wheat, the gap between maximum yield and average yield over extensive areas is smaller compared to most other crops.

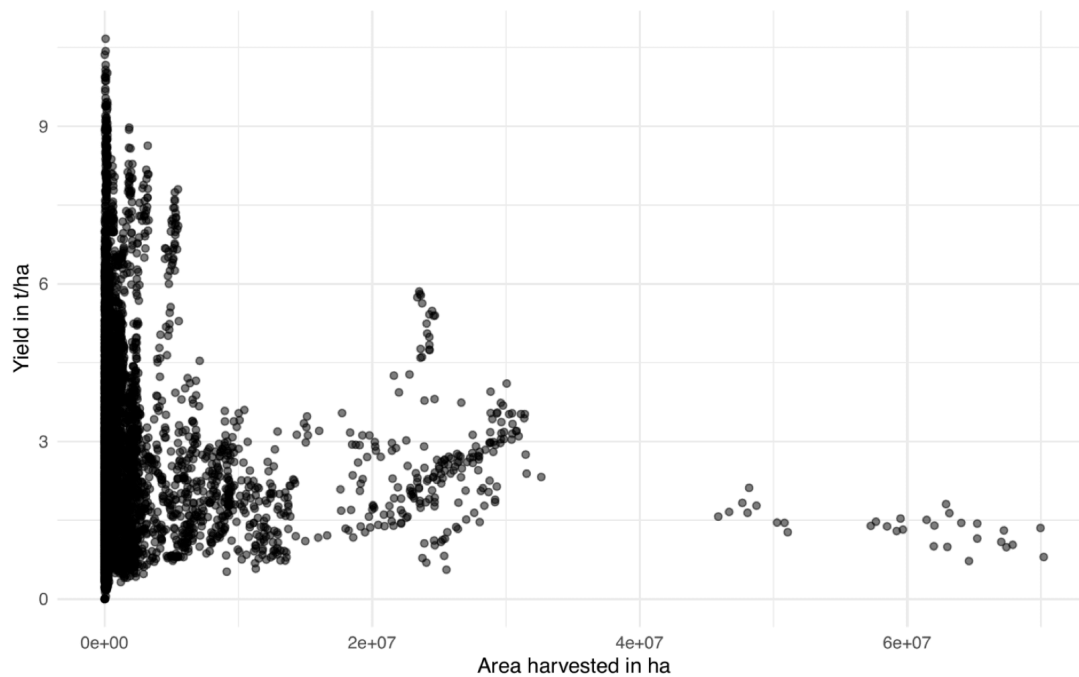


Figure 10. Hectare yield plotted against area harvested for wheat from 1961 to 2023. Each data point represents a country-year observation for this period.

Tomatoes (see Fig. 11) exemplify a typical "L chart type 1" crop. In this case, the highest yields are consistently found in countries or regions with comparatively small harvested areas, often under specialized or intensive management conditions. When tomato production is expanded to larger areas, the average yields tend to decrease noticeably, illustrating the limited scalability of the highest yield levels for this crop.

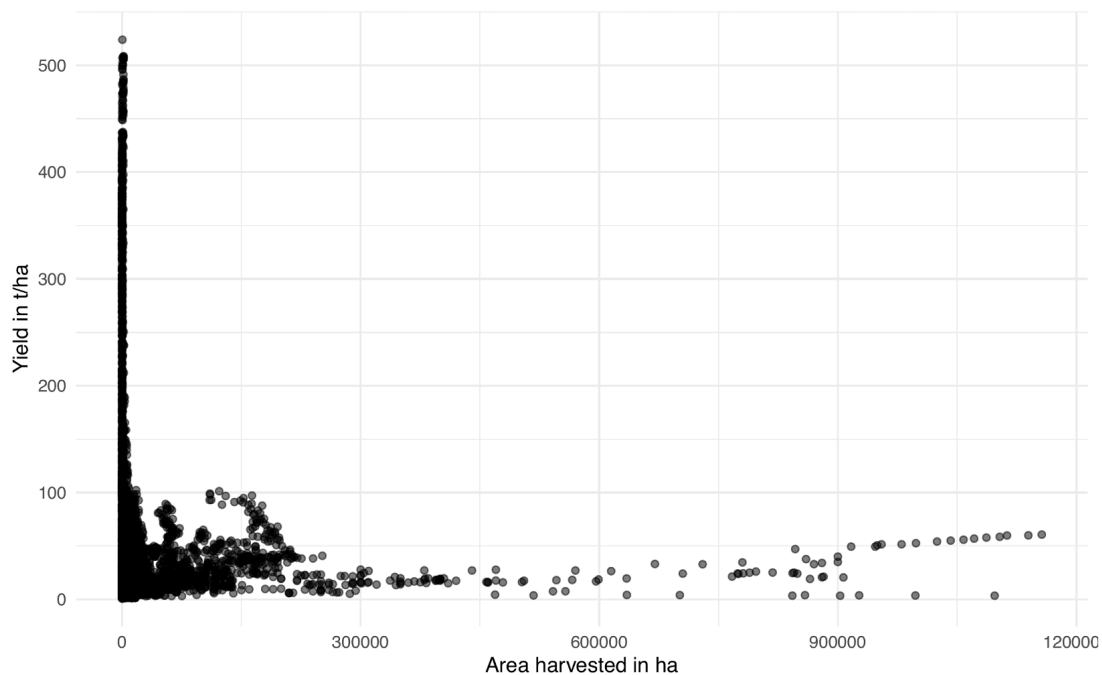


Figure 11. Hectare yield plotted against area harvested for tomatoes from 1961 to 2023. Each data point represents a country-year observation for this period.

It is important to note that crops assigned to "L chart type 2" also do not allow for simple scaling up of maximum yields to large harvested areas. While they may display high yields in a somewhat broader range of conditions than type 1 crops, the pattern generally remains: maximum yields tend to be confined to more restricted production contexts, and the transfer of these yields to the full cultivation area is not possible without significant reductions.

A detailed visualization of the "L chart" of all 157 crops analyzed can be found in the supplementary material.

In this classification scheme, crop diagrams were grouped into five types based on the distribution of data points in the yield-area plane. "L chart type 1" crops are characterized by high yields concentrated in small harvested areas, while higher types indicate greater scalability of high yields to larger areas (see Fig. 12 for examples).

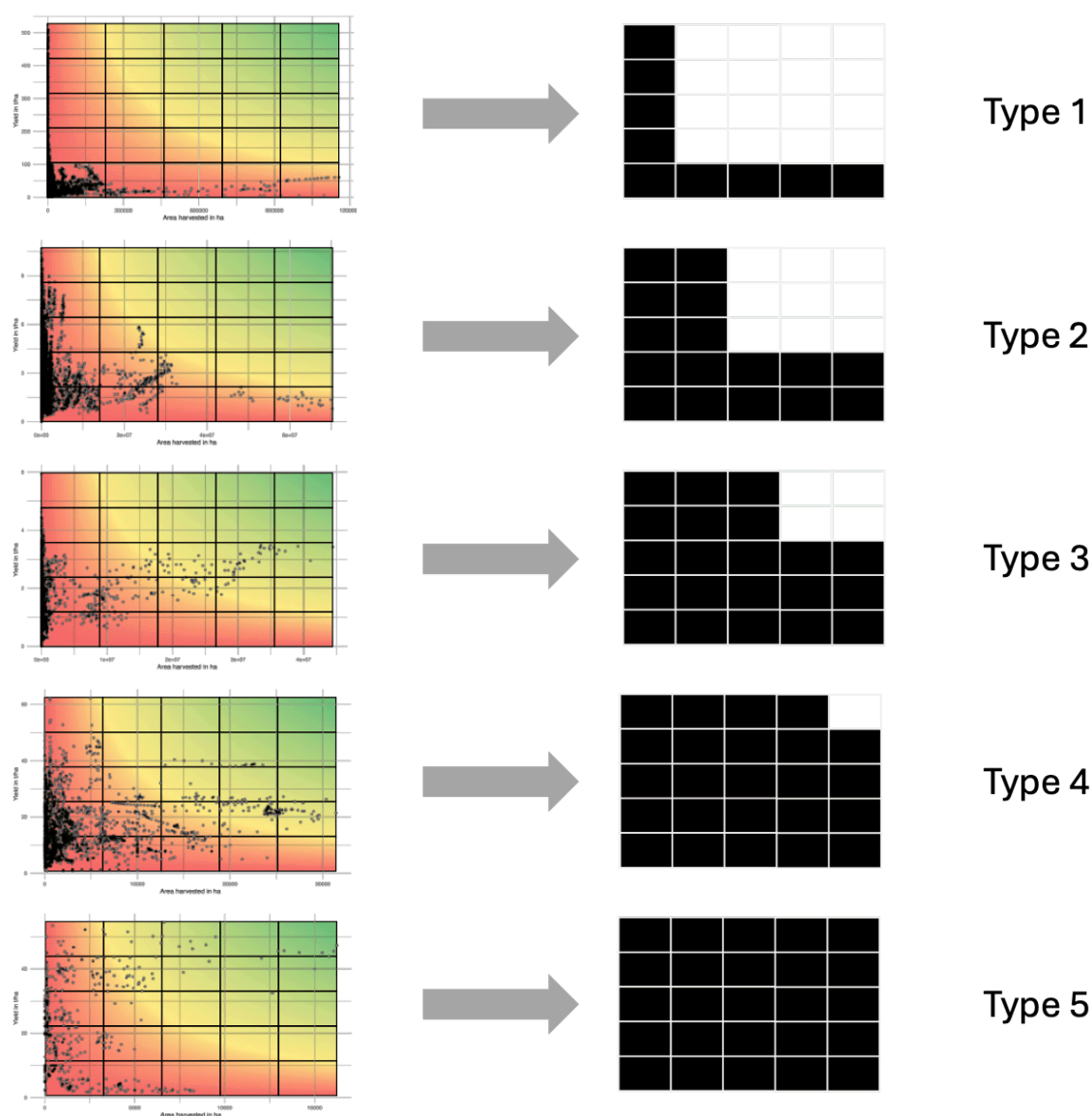


Figure 12. Example classification of yield evolution diagrams (see text for detailed description). From top to bottom: tomatoes, wheat, soybeans, onions and shallots (green), chicory roots.

The aggregated results of this analysis are presented in Fig. 13 and Tab. 3. Of the 157 crops examined, approximately 86% exhibit a type 1 and type 2 distribution, where maximum yields are limited to small-scale cultivation and are not realized at larger scales. These crops account for more than 90% of global production volume. Only a small fraction of crops (type 5) demonstrates the ability to combine both large harvested area and high yield; these account for less than 1% of crop count contribute a very low share (0.0003%) to global production volume.

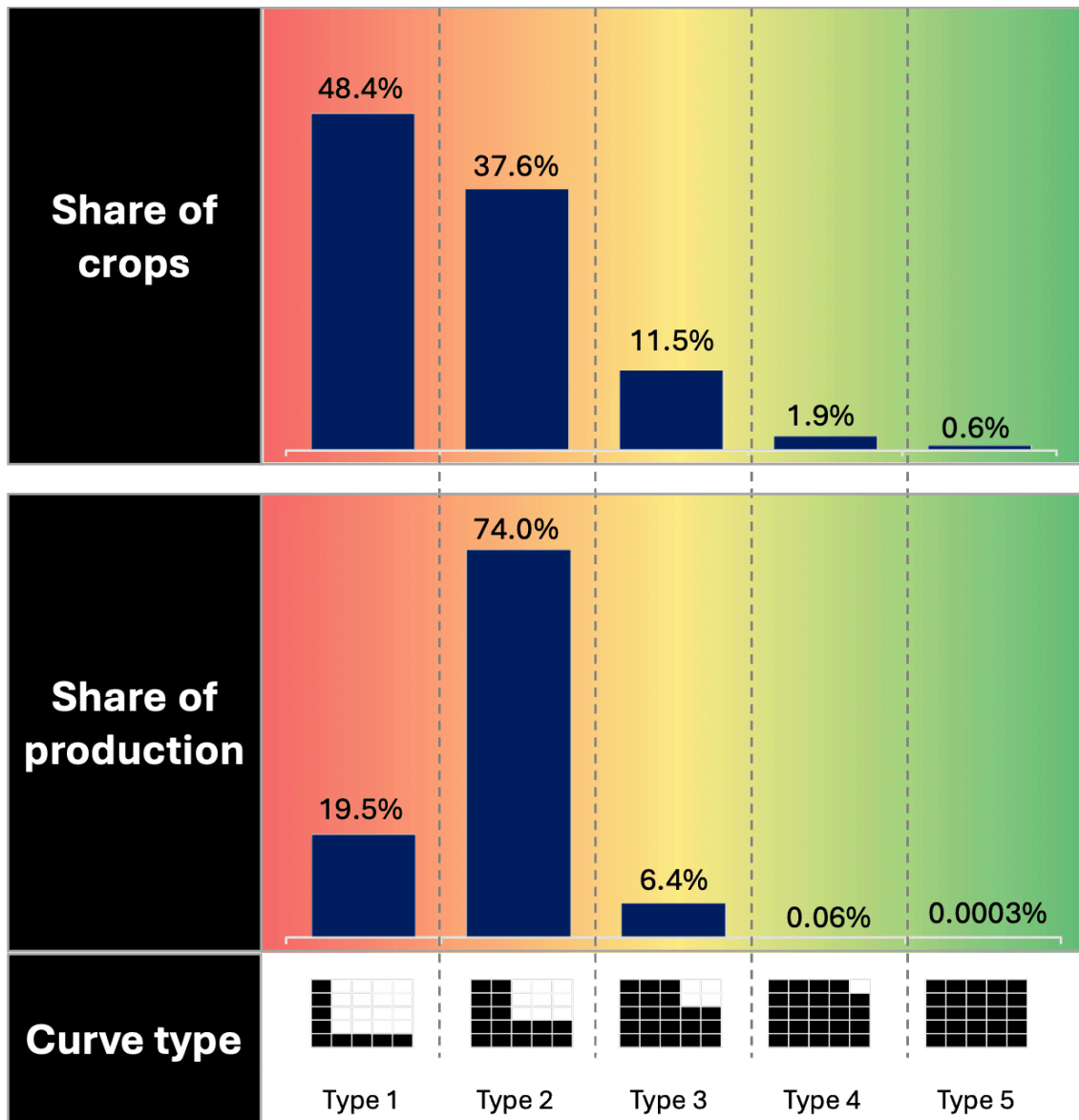


Figure 13. Classification of “yield vs. area harvested” diagrams for all 157 crops in the FAO database according to the approach described in the text. Top: share of crops (number of crops in each category divided by total number of crops). Bottom: share of production (production volume per category divided by total production volume).

Curve Type	Type 1	Type 2	Type 3	Type 4	Type 5
Number of crops	76 (48.4%)	59 (37.6%)	18 (11.5%)	3 (1.9%)	1 (0.6%)
Share of production volume 2023	19.5%	74.0%	6.4%	0.06%	0.0003%
	Abaca (manila hemp (raw), Almonds (in shell), Anise / badian / coriander / cumin / caraway / fennel and juniper berries (raw), Apples, Areca nuts, Asparagus, Barley, Beans (dry), Broad beans and horse beans (dry), Cantaloupes and other melons, Cashew nuts in shell, Cauliflowers and broccoli, Cereals, Cherries, Chick peas (dry), Chillies and peppers (dry, raw), Chillies and peppers (green), Cloves (whole stems, raw), Cocoa beans, Coconuts in shell, Coffee (green), Cow peas (dry), Cranberries, Cucumbers and gherkins, Eggplants (aubergines), Figs, Flax (raw or retted), Ginger (raw), Groundnuts (excluding shelled Hazelnuts) in shell, Hempseed, Jute (raw or retted), Kenaf and other textile bast fibres (raw or retted), Leeks and other alliaceous vegetables, Unseed, Locust beans (carobs), Mangoes / javas and mangosteens, Melonseed, Millet, Mustard seed, Nutmeg / mace / cardamoms (raw), Oliva, Olives, Other fibre crops (raw), Other fruits, Other nuts (excluding wild edible nuts and groundnuts) in shell, Other oil seeds, Other pulses, Other stimulant / spice and aromatic crops, Other sugar crops, Other vegetables (fresh), Papayas, Pears, Pepper (raw), Persimmons, Pigeon peas (dry), Plantains and cooking bananas, Plums and sloes, Poppy seed, Pumpkins / squash and gourds, Quinces, Sesame seed, Sisal (raw), Sorghum, Sour cherries, Tangerines / mandarins (Clementines, Taro, Tomatoes, True hemp (raw or retted), Unmanufactured tobacco, Vanilla (raw), Vetches, Walnuts in shell, Watermelons, Yams, Yautia	Apricots, Artichokes, Avocados, Bambara beans (dry), Bananas, Broad beans and horse beans (green), Buckwheat, Cabbages, Carrots and turnips, Cashewapple, Cassava (fresh), Chestnuts (in shell), Cinnamon and cinnamon-tree flowers (raw), Currants, Dates, Edible roots and tubers with high starch or inulin content (fresh), Fonio, Gooseberries, Green garlic, Kapok fruit, Karite nuts (sheanuts), Kiwi fruit, Lemons and limes, Lentils (dry), Lettuce and chicory, Lupins, Maize (corn), Matté leaves, Mixed grain, Oats, Oil palm fruit, Onions and shallots (dry, excluding dehydrated), Oranges, Other citrus fruit, Other pome fruits, Other stone fruits, Other tropical fruits, Peas (dry), Peas (green), Pineapples, Pistachios (in shell), Potatoes, Pyrethrum (dried flowers), Ramié (raw or retted), Raspberries, Rice, Rye, Safflower seed, Seed cotton (unginned), Spinach, Strawberries, String beans, Sugar beet, Sugar cane, Sunflower seed, Sweet potatoes, Tea leaves, Tung nuts, Wheat	Blueberries, Canary seed, Castor oil seeds, Grapes, Green corn (maize), Hop cones, Jojoba seeds, Kola nuts, Natural rubber in primary forms, Other beans (green), Other berries and fruits of the genus Vaccinium, Peaches and nectarines, Peppermint / spearmint, Pomekio and grapefruits, Quinoa, Rape or colza seed, Soya beans, Triticale	Agave fibres (raw), Onions and shallots (green), Tallowtree seeds	Chicory roots
Crops					

Table 3. Results of L chart type classification for 157 crops in 2023.

This distribution indicates that, for most crops, high yields are attainable only under restricted conditions or in limited regions, and have not been widely replicated at scale. Conversely, a select subset of crops – typically major staple grains – are able to sustain high yields over extensive cultivation areas.

The data thus suggest a general limitation in translating maximum achievable yields to broader production systems at the global level. This finding is consistent with the observed divergence between maximum yield trends and weighted global average yield trends described in previous chapters.

4. Discussion

Our analysis of FAOSTAT data shows that yield per hectare for most global crops is expected to continue to rise for the time being. However, we speculate that future increases will not necessarily be of the same magnitude as those observed in previous decades, and it would not be surprising to see yields declining on a larger scale in the coming years. This hypothesis is supported by the declining annual growth rate of yield improvement as well as the observation that an increasing number of crops have reached yield stagnation or are experiencing collapsing yields at the global level – both in terms of average and maximum yield. Notably, 21.7% of global crop production volume was categorized as “yields decreasing” when considering the maximum yield.

Further increases in crop production are thus increasingly unlikely to originate from yield improvements alone, as transferring high yields to large cultivation areas cannot be observed at scale. Consequently, growth in crop production volume will more likely be derived from expansion in the total area harvested, consistent with trends observed over the past two decades (Fig. 2) and previously anticipated by Cassman et al. [28]. While “area harvested” does not precisely correspond to “cultivated area” due to multiple harvest cycles on the same land, these findings are supported by other work projecting further increases in the area under cultivation [14][29]. The latter study also highlights that much of the recent expansion has occurred for high-profit crops (e.g., soybean, oil palm, sugar cane) at the expense of natural ecosystems, including primary rainforest.

The increase in hectare yield observed over the last few decades has been predominantly enabled by intensification measures such as irrigation [30][31][32], mechanization [33][34][35], increased fertilization [31][36][37], and the application of agrochemicals, including pesticides and herbicides [32][38][39], as well as the adoption of genetically modified crops [40][41][42]. Central to these developments is rising energy consumption within the global crop production system – a phenomenon widely discussed and quantified in the literature [43][44][45][46][47][48][49][50]. The greatest components of agricultural energy demand are usually attributable to fuel and

fertilizer use ^{[45][51]}, or to the provision of heating, cooling, and electricity in greenhouse cultivation ^[52]. In this context, declining EROEI (energy return on energy invested) for fossil fuels – which remain critical to crop production infrastructure – may pose a risk of systemic collapse ^{[4][53][54][55][56]}.

In addition to these existing challenges, crop yields face increasing stress arising from accelerating climate change – manifested by more frequent droughts, heavy rainfall events, heat waves, or late frost episodes ^[57]. These factors can reduce yields despite ongoing intensification, as reported by several studies ^{[4][58][59][60][61][62][63]}. Indeed, several crops in our dataset exhibit such developments – cocoa beans, for instance, have experienced a decline in maximum yield in recent years due to crop failures in major producing countries ^[64].

To secure future food supply for a growing world population, there is thus a need for strategies which can increase yields at scale. While a comprehensive literature review on this topic was not performed here, potential avenues include the optimization of crop growing periods ^[65] and improvements in the efficiency of photosynthesis and respiration ^[66]. However, it remains unclear whether these approaches will be sufficient, given that decades of research have not produced the yield gains once hoped for.

It is important to emphasize that our high-level analysis of aggregated data on a global level does not allow for precise prediction of specific trends for individual crops or countries. Nonetheless, we hope that this work provides a broader overview to inform policy-makers, researchers, farmers, and stakeholders in agribusiness in their decisions going forward.

Given the limitations and risks outlined above, the focus should shift increasingly towards systemic approaches that do not rely solely on expanding yields or cultivated area. As highlighted by Winkler et al. ^[29] and others, halting the conversion of natural ecosystems and rainforests for agricultural expansion will be essential. Equally important is the reduction of food loss and waste along the entire supply chain, as substantial portions of global harvest are not utilized for human nutrition ^[67]. Dietary transitions toward greater consumption of vegetables and plant-based foods, and correspondingly lower intake of animal products, have repeatedly been shown to reduce overall resource use and environmental pressure ^{[68][69]}. These measures, alongside improvements in food system efficiency and equity, offer opportunities to address food security challenges without exacerbating land and energy constraints.

5. Conclusions

This study provides a comprehensive assessment of trends in global crop yield and harvested area for 157 major crops using FAOSTAT data. Current patterns show that, while acute limits to overall growth are not yet observable for global crop production, the rate of yield improvement is slowing, and the majority of crops are exhibiting signs of stagnation or even decrease with respect to their maximum yields. Increases in total output

have recently been achieved more by expanding harvested area than by transferring high yields to larger cultivation scales. However, such expansion often comes at significant ecological costs, including deforestation and loss of natural ecosystems, and may not be sustainable in the long term.

Climate change is expected to exert further pressure on yields, introducing greater variability and the risk of systematic declines or even collapses for some crops. The increasing reliance on energy-intensive inputs, alongside potential limits to available fossil energy, adds another layer of vulnerability to agricultural systems.

Given these intersecting constraints, future strategies for global food security should move beyond a narrow focus on yield intensification or land expansion. Reducing food loss and waste offers considerable potential: currently, up to one-third of all globally produced food is estimated to be lost or wasted ^{[22][67][70][71]}, representing a significant opportunity for efficiency gains across the entire supply chain.

In addition, dietary shifts towards more plant-based foods and reduced reliance on animal-based products – particularly ruminant meat – can lower the resource intensity of food production, decrease land and energy requirements, and support both environmental sustainability and resilience ^{[69][72][73]}. Promoting plant-rich diets not only mitigates the need for continual crop yield increases but also provides co-benefits for public health and climate protection.

In summary, the path towards sustainable global food systems will require an integrated approach: moderating production demands through systemic changes in consumption patterns, significant reductions in food waste, and careful stewardship of remaining agricultural land. Only through a combination of these measures will it be possible to ensure food security in a world of constrained yields and changing climate.

For policymakers, researchers, farmers, and actors across the food system, this means a shift in perspective: the focus must broaden from maximizing agricultural output to enhancing resource efficiency, equity, and resilience. Achieving this transformation will require coordinated efforts at local, national, and international levels, embracing innovation, behavioral change, and the protection of planetary boundaries. The challenge is substantial, but by rethinking priorities and harnessing collective action, the foundation for sustainable nourishment and ecosystem health can be secured for generations to come.

References

1. [△]Miladinov G (2023). "Impacts of Population Growth and Economic Development on Food Security in Low-Income and Middle-Income Countries." *Front Hum Dyn.* 5:1121662. doi:[10.3389/fhumd.2023.1121662](https://doi.org/10.3389/fhumd.2023.1121662).
2. [△][△]van Dijk M, Morley T, Rau ML, Saghai Y (2021). "A Meta-Analysis of Projected Global Food Demand and Population at Risk of Hunger for the Period 2010–2050." *Nat Food.* 2:494–501. doi:[10.1038/s43016-021-00322-9](https://doi.org/10.1038/s43016-021-00322-9).

3. [△]Schneider UA, Havlík P, Schmid E, Valin H, Mosnier A, Obersteiner M, Böttcher H, Skalský R, Balkovič J, Sauer T, Fritz S (2011). "Impacts of Population Growth, Economic Development, and Technical Change on Global Food Production and Consumption." *Agric Syst.* **104**:204–215. doi:[10.1016/j.agsy.2010.11.003](https://doi.org/10.1016/j.agsy.2010.11.003).
4. [△][△] [△]Rasul K, Bruckner M, Mempel F, Tsrek S, Hertwich EG (2024). "Energy Input and Food Output: The Energy Imbalance Across Regional Agrifood Systems." *PNAS Nexus.* **3**:pgae524. doi:[10.1093/pnasnexus/pgae524](https://doi.org/10.1093/pnasnexus/pgae524).
5. [△]FAO (2024). "World Food and Agriculture – Statistical Yearbook 2024." FAO. doi:[10.4060/cd2971en](https://doi.org/10.4060/cd2971en).
6. [△][△] [△]Ray DK, Ramankutty N, Mueller ND, West PC, Foley JA (2012). "Recent Patterns of Crop Yield Growth and Stagnation." *Nat Commun.* **3**:1293. doi:[10.1038/ncomms2296](https://doi.org/10.1038/ncomms2296).
7. [△]Johnson DG (1999). "The Growth of Demand Will Limit Output Growth for Food Over the Next Quarter Century." *Proc Natl Acad Sci USA.* **96**:5915–5920.
8. [△]Malthus T (1798). *An Essay on the Principle of Population*. London: J Johnson.
9. [△]Ehrlich P (1968). *The Population Bomb*. New York: Ballantine Books.
10. [△][△] [△]Meadows DH, Meadows DL, Randers J, Behrens WW III (1972). *The Limits to Growth: A Report for the Club of Rome's Project on the Predicament of Mankind*. New York: Universe Books.
11. [△]Linehan V, Thorpe S, Gunning-Trant C, Heyhoe E, Harle K, Hormis M, Harris-Adam K (2013). "Global Food Production and Prices to 2050: Scenario Analysis Under Policy Assumptions." ABARES. <https://www.agriculture.gov.au/sites/default/files/sitecollectiondocuments/abares/publications/globeFoodProd2050v1.0.1.pdf> [accessed 2025 Oct 3].
12. [△]Tilman D, Balzer C, Hill J, Belfort BL (2011). "Global Food Demand and the Sustainable Intensification of Agriculture." *Proc Natl Acad Sci USA.* **108**(50):20260–20264.
13. [△]Ray DK, Mueller ND, West PC, Foley JA (2013). "Yield Trends Are Insufficient to Double Global Crop Production by 2050." *PLOS ONE.* **8**(6):e66428.
14. [△][△] [△]Balmford A, Green RE, Scharlemann JPW (2005). "Sparing Land for Nature: Exploring the Potential Impact of Changes in Agricultural Yield on the Area Needed for Crop Production." *Glob Change Biol.* **11**:1594–1605.
15. [△]Forrester J (1958). "Industrial Dynamics: A Major Breakthrough for Decision Makers." *Harvard Bus Rev.* **36**:37–66.
16. [△]Forrester J (1961). *Industrial Dynamics*. Cambridge: MIT Press.
17. [△]Forrester J (1968). *Principles of Systems*. Portland: Productivity Press.
18. [△]Meadows DH (2008). *Thinking in Systems: A Primer*. White River Junction: Chelsea Green.
19. [△]Bardi U (2013). "Mind Sized World Models." *Sustainability.* **5**:896–911. doi:[10.3390/su5030896](https://doi.org/10.3390/su5030896).
20. [△]Inghels D (2020). "Structure and Fundamental Modes of Behavior in Dynamic Systems." In: Inghels D, editor. *Introduction to Modeling Sustainable Development in Business Processes*. Cham: Springer. p.154–64. doi:[10.1007/978-3-030-58422-1_9](https://doi.org/10.1007/978-3-030-58422-1_9).

21. ^AGerber JS, Ray DK, Makowski D, Butler EE, Mueller ND, West PC, Johnson JA, Polasky S, Samberg LH, Siebert S, Sloat L (2024). "Global Spatially Explicit Yield Gap Time Trends Reveal Regions at Risk of Future Crop Yield Stagnation." *Nat Food*. 5:125–135.
22. ^A^BTian X, Engel BA, Qian H, Hua E, Sun S, Wang Y (2021). "Will Reaching the Maximum Achievable Yield Potential Meet Future Global Food Demand?" *J Clean Prod*. 294:126285. doi:[10.1016/j.jclepro.2021.126285](https://doi.org/10.1016/j.jclepro.2021.126285).
23. ^AGrassini P, Eskridge KM, Cassman KG (2013). "Distinguishing Between Yield Advances and Yield Plateaus in Historical Crop Production Trends." *Nat Commun*. 4:2918. doi:[10.1038/ncomms3918](https://doi.org/10.1038/ncomms3918).
24. ^ACleveland WS, Devlin SJ (1988). "Locally Weighted Regression: An Approach to Regression Analysis by Local Fitting." *J Am Stat Assoc*. 83:596–610.
25. ^ANational Institute of Standards and Technology (NIST) (2012). "LOESS (aka LOWESS), NIST/SEMATECH e-Handbook of Statistical Methods, Chapter 4.1.4.4." National Institute of Standards and Technology (NIST). <https://www.itl.nist.gov/div898/handbook/pmd/section1/pmd144.htm> [accessed 2025 Jul 30].
26. ^Avan Ittersum MK, Cassman KG, Grassini P, Wolf J, Tittonell P, Hochman Z (2013). "Yield Gap Analysis With Local to Global Relevance – A Review." *Field Crops Res*. 143:4–17. doi:[10.1016/j.fcr.2012.09.009](https://doi.org/10.1016/j.fcr.2012.09.009).
27. ^Avan Wart J, Kersebaum KC, Peng S, Milner M, Cassman KC (2013). "Estimating Crop Yield Potential at Regional to National Scales." *Field Crops Res*. 143:34–43.
28. ^ACassman KG, Dobermann AR, Walters DT, Yang H (2003). "Meeting Cereal Demand While Protecting Natural Resources and Improving Environmental Quality." *Annu Rev Environ Resour*. 28:315–358. doi:[10.1146/annurev.energy.28.040202.122858](https://doi.org/10.1146/annurev.energy.28.040202.122858).
29. ^A^BWinkler K, Fuchs R, Rounsevell M, Herold M (2025). "Six Decades of Global Crop Yield Increase and Cropland Expansion From 1960 to 2020." *Environ Res Commun*. 7:055013. doi:[10.1088/2515-7620/add3](https://doi.org/10.1088/2515-7620/add3).
30. ^ARockström J, Karlberg L, Wani SP, Barron J, Hatibu N, Oweis T, Bruggeman A, Farahini J, Qiang Z (2010). "Managing Water in Rainfed Agriculture – The Need for a Paradigm Shift." *Agric Water Manag*. 97:543–550. doi:[10.1016/j.agwat.2009.09.009](https://doi.org/10.1016/j.agwat.2009.09.009).
31. ^A^BXing Y, Wang X (2024). "Precise Application of Water and Fertilizer to Crops: Challenges and Opportunities." *Front Plant Sci*. 15:1444560. doi:[10.3389/fpls.2024.1444560](https://doi.org/10.3389/fpls.2024.1444560).
32. ^A^BShekar C (2025). "The Role of Agrochemicals in the Field of Agriculture and Irrigation of Crop Yields for Growth of Food Production." *J Agric Food Res*. 16:197. doi:[10.35248/2593-9173.25.16.197](https://doi.org/10.35248/2593-9173.25.16.197).
33. ^AGebiso T, Ketema M, Shumetie A, Feye GL (2024). "Impact of Farm Mechanization on Crop Productivity and Economic Efficiency in Central and Southern Oromia, Ethiopia." *Front Sustain Food Syst*. 8:1414912. doi:[10.3389/fsufs.2024.1414912](https://doi.org/10.3389/fsufs.2024.1414912).

34. [△]Madzivanzira T, Mvumi BM, Nazare RM, Nyakudya E, Mtambanengwe F, Mapfumo P (2024). "A Review of Appropriate Mechanisation Systems for Sustainable Traditional Grain Production by Smallholder Farmers in Sub-Saharan Africa With Particular Reference to Zimbabwe." *Heliyon*. **10**:e36695. doi:[10.1016/j.heliyon.2024.e36695](https://doi.org/10.1016/j.heliyon.2024.e36695).
35. [△]Houmy K, Clarke LJ, John E, Ashburner JE, Kienzle J (2013). "Agricultural Mechanization in Sub-Saharan Africa: Guidelines for Preparing a Strategy." In: Plant Production and Protection Division (eds). *Integrated Crop Management* 22. Rome: Food and Agriculture Organization of the United Nations.
36. [△]Liu Q, Xu H, Yi H (2021). "Impact of Fertilizer on Crop Yield and C:N:P Stoichiometry in Arid and Semi-Arid Soil." *Int J Environ Res Public Health*. **18**:4341. doi:[10.3390/ijerph18084341](https://doi.org/10.3390/ijerph18084341).
37. [△]Zhang L, Yuan J, Zhang M, Zhang Y, Wang L, Li J (2022). "Long Term Effects of Crop Rotation and Fertilization on Crop Yield Stability in Southeast China." *Sci Rep*. **22**:14234. doi:[10.1038/s41598-022-17675-1](https://doi.org/10.1038/s41598-022-17675-1).
38. [△]Nishimoto R (2019). "Global Trends in the Crop Protection Industry." *J Pestic Sci*. **44**(3):141–147. doi:[10.1584/jpestics.D19-101](https://doi.org/10.1584/jpestics.D19-101).
39. [△]Tobi M, Raj A, Banu F, Sreelekshmi M, Sajeev B (2025). "Chemical Drivers of Crop Development: A Review on Agrochemical Interventions." *Int J Adv Biochem Res*. **SP-9**(9):289–299. doi:[10.33545/26174693.2025.v9.i9Sd.5508](https://doi.org/10.33545/26174693.2025.v9.i9Sd.5508).
40. [△]Pellegrino E, Bedini S, Nuti M, Ercoli L (2018). "Impact of Genetically Engineered Maize on Agronomic, Environmental and Toxicological Traits: A Meta-Analysis of 21 Years of Field Data." *Sci Rep*. **8**:3113. doi:[10.1038/s41598-018-21284-2](https://doi.org/10.1038/s41598-018-21284-2).
41. [△]Raman R (2017). "The Impact of Genetically Modified (GM) Crops in Modern Agriculture: A Review." *GM Crops Food*. **8**:195–208. doi:[10.1080/21645698.2017.1413522](https://doi.org/10.1080/21645698.2017.1413522).
42. [△]Kovak E, Blaustein-Rejto D, Qaim M (2022). "Genetically Modified Crops Support Climate Change Mitigation." *Trends Plant Sci*. **27**(7):627–629.
43. [△]Elsoragaby S, Yahya A, Mahadi MR, Nawawi NM, Mairghany M (2019). "Energy Utilization in Major Crop Cultivation." *Energy*. **173**:1285–1303. doi:[10.1016/j.energy.2019.01.142](https://doi.org/10.1016/j.energy.2019.01.142).
44. [△]Kargwal R, Yadavika, Kumar A, Garg MK, Chanakaewsomboon I (2022). "A Review on Global Energy Use Patterns in Major Crop Production Systems." *Environ Sci Adv*. **1**:662.
45. [△]^aYuan S, Peng S (2017). "Input-Output Energy Analysis of Rice Production in Different Crop Management Practices in Central China." *Energy*. **141**:1124–1132. doi:[10.1016/j.energy.2017.10.007](https://doi.org/10.1016/j.energy.2017.10.007).
46. [△]Khambalkar V, Pohare J, Katkhede S, Bunde D, Dahatonde S (2010). "Energy and Economic Evaluation of Farm Operations in Crop Production." *J Agric Sci*. **2**(4):191.
47. [△]Smil V (2022). *How the World Really Works: The Science Behind How We Got Here and Where We're Going*. London: Penguin.

48. ^ΔEurostat (2025). "Agri-Environmental Indicator – Energy Use." Eurostat. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri-environmental_indicator_-_energy_use [accessed 2025 Oct 3].
49. ^ΔOECD, Food and Agriculture Organization of the United Nations (2025). "OECD-FAO Agricultural Outlook 2025-2034." OECD/FAO. doi:[10.1787/601276cd-en](https://doi.org/10.1787/601276cd-en).
50. ^ΔHall CAS (2022). "The 50th Anniversary of The Limits to Growth: Does It Have Relevance for Today's Energy Issues?" *Energies*. **15**:4953. doi:[10.3390/en15144953](https://doi.org/10.3390/en15144953).
51. ^ΔErdal G, Esengün K, Erdal H, Gündüz O (2007). "Energy Use and Economical Analysis of Sugar Beet Production in Tokat Province of Turkey." *Energy*. **32**:35–41.
52. ^ΔParis B, Vadorou F, Balafoutis AT, Vaiopopulos K, Kyriakarakos G, Manolakis D, Papadakis G (2022). "Energy Use in Greenhouses in the EU: A Review Recommending Energy Efficiency Measures and Renewable Energy Sources Adoption." *Appl Sci*. **12**:5150. doi:[10.3390/app12105150](https://doi.org/10.3390/app12105150).
53. ^ΔPerissi I, Lavacchi A, Bardi U (2021). "The Role of Energy Return on Energy Invested (EROEI) in Complex Adaptive Systems." *Energies*. **14**:8411. doi:[10.3390/en14248411](https://doi.org/10.3390/en14248411).
54. ^ΔHagens NJ (2020). "Economics for the Future – Beyond the Superorganism." *Ecol Econ*. **169**:106520. doi:[10.1016/j.ecolecon.2019.106520](https://doi.org/10.1016/j.ecolecon.2019.106520).
55. ^ΔHall CAS, Klitgaard K (2018). *Energy and the Wealth of Nations*. 2nd ed. Cham: Springer.
56. ^ΔMurphy D (2014). "The Implications of the Declining Energy Return on Investment of Oil Production." *Phil Trans R Soc A*. **372**:20130126. doi:[10.1098/rsta.2013.0126](https://doi.org/10.1098/rsta.2013.0126).
57. ^ΔHeilemann J, Klassert C, Samaniego L, Thober S, Marx A, Boeing F, Klauer B, Gawel E (2024). "Projecting Impacts of Extreme Weather Events on Crop Yields Using LASSO Regression." *Weather Clim Extrem*. **46**:100738. doi:[10.1016/j.wace.2024.100738](https://doi.org/10.1016/j.wace.2024.100738).
58. ^ΔHu T, Zhang X, Khanal S, Wilson R, Leng G, Toman EM, Wang X, Li Y, Zhao K (2024). "Climate Change Impacts on Crop Yields: A Review of Empirical Findings, Statistical Crop Models, and Machine Learning Methods." *Environ Model Softw*. **179**:106119. doi:[10.1016/j.envsoft.2024.106119](https://doi.org/10.1016/j.envsoft.2024.106119).
59. ^ΔHultgren A, Carleton T, Delgado M, Gergel DR, Greenstone M, Houser T, Hsiang S, Jina A, Kopp RE, Malevich SB, McCusker KE, Mayer T, Nath I, Rising J, Rode A, Yuan J (2025). "Impacts of Climate Change on Global Agriculture Accounting for Adaptation." *Nature*. **642**:644–652. doi:[10.1038/s41586-025-09085-w](https://doi.org/10.1038/s41586-025-09085-w).
60. ^ΔOdeyomi OA, Ejimakor G, Isikhuemhen OS (2024). "Effects of Climate Change on Crop Yield: Is It a Benefit or Menace?" *Eur Sci J*. **20**(30):1. doi:[10.19044/esj.2024.v20n30p1](https://doi.org/10.19044/esj.2024.v20n30p1).
61. ^ΔPeng S, Huang J, Sheehy JE, Laza RC, Vesperas RM, Zhong X, Centeno GS, Khush GS, Cassman KG (2004). "Rice Yields Decline With Higher Night Temperature From Global Warming." *Proc Natl Acad Sci USA*. **101**(27):9971–9975.

62. [△]Rezaei EE, Webber H, Asseng S, Boote K, Durand JL, Ewert F, Martre P, MacCarthy DS (2023). "Climate Change Impacts on Crop Yields." *Nat Rev Earth Environ.* 4:831–846.
63. [△]Zhao C, Liu B, Piao S, Wang X, Lobell DB, Huang Y, Huang M, Yao Y, Bassu S, Ciais P, Durand JL, Elliott J, Ewert F, Janssens IA, Li T, Lin E, Liu Q, Martre P, Müller C, Peng S, Peñuelas J, Ruane AC, Wallach D, Wang T, Wu D, Liu Z, Zhu Y, Asseng S (2017). "Temperature Increase Reduces Global Yields of Major Crops in Four Independent Estimates." *Proc Natl Acad Sci USA.* 114(35):9326–9331. doi:[10.1073/pnas.1701762114](https://doi.org/10.1073/pnas.1701762114).
64. [△]Adesina O (2024). "Cocoa Prices Hit Records as West African Yields Decline." *Afr Bus.* <https://african.business/2024/04/resources/cocoa-prices-hit-records-as-west-african-yields-decline> [accessed 2025 Oct 3].
65. [△]Minoli S, Jägermeyr J, Asseng S, Urfels A, Müller C (2022). "Global Crop Yields Can Be Lifted by Timely Adaptation of Growing Periods to Climate Change." *Nat Commun.* 13:7079. doi:[10.1038/s41467-022-34411-5](https://doi.org/10.1038/s41467-022-34411-5).
66. [△]Garcia A, Gaju O, Bowerman AF, Buck SA, Evans JR, Furbank RT, Gilliam M, Millar AH, Pogson BJ, Reynolds MP, Ruan YL, Taylor NL, Tyerman SD, Atkin OK (2022). "Enhancing Crop Yields Through Improvements in the Efficiency of Photosynthesis and Respiration." *New Phytol.* 237:60–77. doi:[10.1111/nph.18545](https://doi.org/10.1111/nph.18545).
67. [△]^bGustavsson J, Cederberg C, Sonesson U, van Otterdijk R, Meybeck A (2011). *Global Food Losses and Food Waste: Extent, Causes and Prevention*. Rome: Food and Agriculture Organization of the United Nations. <https://www.fao.org/4/mb060e/mb060e00.pdf> [accessed 2025 Oct 3].
68. [△]Poore J, Nemecek T (2018). "Reducing Food's Environmental Impacts Through Producers and Consumers." *Science.* 360:987–992.
69. [△]^bSpringmann M, Godfray HCJ, Rayner M, Scarborough P (2016). "Analysis and Valuation of the Health and Climate Change Cobenefits of Dietary Change." *Proc Natl Acad Sci USA.* 113(15):4146–4151.
70. [△]FAO (2019). "The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction." FAO. <http://openknowledge.fao.org/server/api/core/bitstreams/11f9288f-dc78-4171-8d02-92235b8d7dc7/content> [accessed 2025 Oct 3].
71. [△]Onyeaka H, Tamasiga P, Nwauzoma UM, Miri T, Juliet UC, Nwaiwu O, Akinsemolu AA (2023). "Using Artificial Intelligence to Tackle Food Waste and Enhance the Circular Economy: Maximising Resource Efficiency and Minimising Environmental Impact: A Review." *Sustainability.* 15:10482. doi:[10.3390/su151310482](https://doi.org/10.3390/su151310482).
72. [△]Tilman D, Clark M (2014). "Global Diets Link Environmental Sustainability and Human Health." *Nature.* 515:518–522. doi:[10.1038/nature13959](https://doi.org/10.1038/nature13959).
73. [△]Willett W, Rockström J, Loken B, Springmann M, Lang T, Vermeulen S, Garnett T, Tilman D, DeClerck F, Wood A, Jonell M, Clark M, Gordon LJ, Fanzo J, Hawkes C, Zurayk R, Rivera JA, De Vries W, Majele Sibanda L, Afshin A, Chaudhary A, Herrero M, Agustina R, Branca F, Lartey A, Fan S, Crona B, Fox E, Bignet V, Troell M, Lindahl T, Singh S, Cornell SE, Reddy KS, Narain S, Nishtar S, Murray CJL (2019). "Food in the Anthropocene: The EAT-Lancet Commission on Healthy Diets From Sustainable Food Systems." *Lancet.* 393:447–492. doi:[10.1016/S0140-6736\(18\)31788-4](https://doi.org/10.1016/S0140-6736(18)31788-4).

Supplementary data: available at <https://doi.org/10.32388/89BOX8>

Declarations

Funding: No specific funding was received for this work.

Potential competing interests: No potential competing interests to declare.