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Global crop options for micronutrient output vary by nutrient and place and are unevenly aligned with current monetary production value

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Global crop options for micronutrient output vary by nutrient and place and are unevenly aligned with current monetary production value

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Abstract

Micronutrient inadequacy persists despite gains in food production. Across 213 countries and territories, 48 food crops and 13 micronutrients, attainable yield, nutrient composition and human requirements were integrated to identify crop options for requirement-equivalent nutrient output, with prevalence of inadequate intake as need context. High-ranking options were compared with the current monetary production value (US$ ha^{-1}) of national crop portfolios. First-ranked per-hectare output ranged from 32–36 annual requirements for riboflavin from carrot, iron from soybean and zinc from sunflower, to 1,221 for vitamin A from carrot. Production-value alignment varied across crops and regions, with sunflower and soybean more often incurring high penalties. Eastern Europe and South Asia had the highest aligned shares, whereas penalties were most prominent in Melanesia, Southern Europe and Central Africa. Robustness analyses preserved structural patterns, although ranks were sensitive to nutrient-composition profiles and yield magnitudes differed under external benchmarking. These results identify nutrient- and place-specific crop opportunities requiring agronomic and economic assessment.

Micronutrient inadequacy remains a major global food-system challenge despite sustained growth in food production. Recent estimates suggest that about 5.0 billion people have inadequate calcium intakes, with more than 4 billion having inadequate intakes of iron, riboflavin, folate and vitamin C [1]. These shortfalls vary across nutrients, countries and population groups and can contribute to adverse health and developmental outcomes [2,3]. Their persistence shows that greater food production does not necessarily translate into improved micronutrient adequacy [2,4,5].

This persistence reflects a deeper mismatch between food systems priorities and population micronutrient requirements [6–8]. It is visible in the concentration of global crop production in a narrow set of staples, with maize, rice and wheat together accounting for almost 83% of harvested food calories and 63% of global harvested area [6]. These crops are central to food security, but systems focused primarily on yield, dietary energy and commodity value do not necessarily maximise micronutrient output [7]. Nutritional diversification is therefore meaningful only where alternative crops increase the availability of nutrients that are limiting within a food system [7,8].

The nutritional relevance of alternative crops consequently depends on production context as well as nutrient composition [7–10]. Analyses of plant-based food supplies show that widely produced staple crops may contribute more total nutrients than nutrient-dense alternatives because of the much larger quantities produced, whereas nutrient-rich crops can make only small contributions where production remains limited [10,11]. A crop's potential contribution to population nutrition therefore depends not only on nutrient composition, but also on how much can be produced and where that production is feasible.

At population scale, this production potential is constrained by agro-ecological suitability, attainable yield, spatial alignment with population requirements and compatibility with existing agricultural systems [5,12–14]. The FAO Global Agro-Ecological Zones framework provides spatially explicit estimates of land suitability and attainable crop yields, enabling systematic evaluation of crop production potential across climatic, soil, terrain and management conditions [14]. Because attainable yield varies substantially among locations, nutrient-oriented assessment of crop options must account explicitly for geography [12]. The relevant question is therefore not only which crops contain particular micronutrients, but where those crops can feasibly produce substantial requirement-equivalent nutrient output.

A requirement-centred agricultural assessment must therefore bring together crop nutrient composition, spatial production feasibility and population micronutrient requirement [8,13,14]. Nutrient-gap modelling provides an important benchmark by evaluating food-system output relative to population requirements rather than aggregate food quantity alone [13]. Production decisions, however, also occur within economic and livelihood contexts. Agriculture influences diets through both food availability and income pathways, and nutritionally promising crops may differ substantially from existing crops in estimated production value per hectare [15]. Nutritional and production-value objectives may therefore favour different crop options, highlighting the need to assess nutritional potential alongside current crop-portfolio production value [12–16].

Here, a spatially explicit, requirement-centred framework was developed to integrate crop nutrient composition, attainable yield and population nutrient requirements across 213 countries and territories, 48 food crops and 13 micronutrients. Crops were ranked within each country–nutrient combination using requirement-equivalent nutrient output per hectare, while prevalence of inadequate intake was incorporated as a need-context layer to indicate where high nutrient-output potential coincided with greater estimated population inadequacy. High-ranking crop options were then compared with the current monetary crop-portfolio production-value benchmarks, expressed in US$ ha^{-1}, using matched harvested-area, attainable-yield and producer-price data. This global screen identifies crop–nutrient combinations with high attainable nutrient output, highlights where these opportunities coincide with greater estimated need, and distinguishes cases that align more closely with current production-value conditions from those associated with larger penalties or insufficient economic data.

1. **Results**

1.1. **A requirement-centred nutrient-opportunity layer across feasible crops**

Across 213 countries and territories, 48 food crops and 13 micronutrients, the analysis included 90,688 country–crop–nutrient observations from 6,976 country–crop combinations (Fig. 1; Supplementary Data 2). Per-hectare nutrient output differed markedly among nutrients. Under the reference composition profiles, the first-ranked crop supplied approximately 32–36 annual benchmark requirements ha^{-1} for riboflavin from carrot, iron from soybean and zinc from sunflower, compared with 1,221 for vitamin A from carrot (Fig. 1a). Other first-ranked combinations included sunflower for copper and phosphorus; okra for calcium, folate, magnesium and thiamin; sweet potato for vitamin B_6; and wetland rice for niacin.

Breadth across country-level top-five rankings also varied strongly among crops (Fig. 1b). Okra had the highest frequency, with 1,249 top-five occurrences across 12 nutrients, followed by carrot with 1,117 across 13 nutrients, sunflower with 1,107 across 11 nutrients and tomato with 1,022 across 13 nutrients. Soybean, white potato and maize occurred 765, 747 and 738 times, respectively. Diagnostic profiles showed that top-ranked cases reflected different combinations of nutrient composition, attainable yield and geographic alignment with population inadequacy (Fig. 1c,d). Composition accounted for the largest diagnostic share (45%; 29 cases), followed by need alignment (31%; 20 cases), with yield, stable high output and mixed profiles accounting for the remainder. The top-five set retained for subsequent analyses comprised 13,754 country–crop–nutrient observations, 15.2% of the full analytical set.

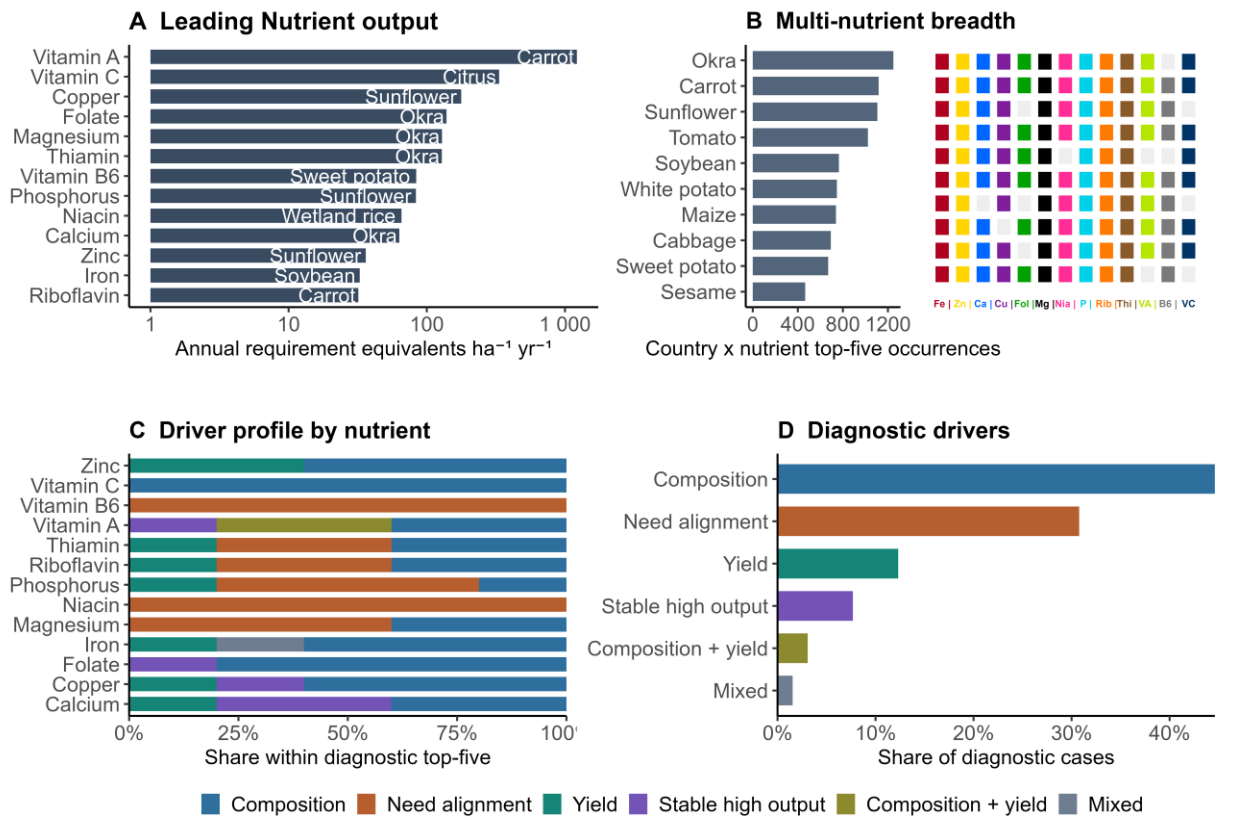

Fig. 1 | Nutrient output, crop breadth and diagnostic ranking profiles across 48 food crops. a, Reference-profile first-ranked crop for each nutrient. Bars show the crop with the highest median requirement-equivalent nutrient output per hectare among the 48 crops, calculated across countries where that crop had attainable yield. Values are expressed as annual benchmark requirements supplied per hectare and shown on a log-scaled x axis. **b**, Multi-nutrient breadth, measured as the number of country–nutrient top-five occurrences in the reference crop rankings. Coloured ticks indicate the nutrients represented by each crop: **Fe**, iron; **Zn**, zinc; **Ca**, calcium; **Cu**, copper; **Fol**, folate; **Mg**, magnesium; **Nia**, niacin; **P,** phosphorus; **Rib**, riboflavin; **Thi**, thiamin; **VA**, vitamin A; **B_6**, vitamin **B_6**; **VC**, vitamin C. **c**, Distribution of diagnostic ranking profiles within the top-five crop set for each nutrient. **d**, Overall distribution of diagnostic profiles among top-ranked crop–nutrient cases. Composition denotes high nutrient-density ranking relative to yield; yield denotes high attainable-yield ranking relative to nutrient density; composition + yield denotes strong ranking for both; stable high output denotes strong ranking before and after PII weighting at the crop–nutrient summary level; need alignment denotes improved ranking after accounting for the geographic distribution of population inadequacy; and mixed denotes cases without a single dominant profile. Full rankings, nutrient membership and diagnostic classifications are provided in Supplementary Data 2 and 3.

1.2. **Nutrient opportunity is geographically structured across countries and subregions**

Country-level rankings showed both widespread and geographically variable crop signals (Fig. 2). Carrot ranked first for vitamin A in 177 of 213 countries and soybean ranked first for iron in 142. Okra ranked first most often for calcium, folate and thiamin, whereas niacin and zinc were distributed across several first-ranked crops. At subregional scale (Extended Data Fig. 2), soybean was frequently first-ranked for iron across sub-Saharan Africa and Asia, okra recurred across calcium, folate, magnesium and thiamin in Africa and South Asia, sunflower was prominent for zinc, phosphorus and thiamin across several European and Asian subregions, and carrot showed a widespread vitamin A signal. These patterns demonstrate that high-ranking crop options were structured by both nutrient and geography.

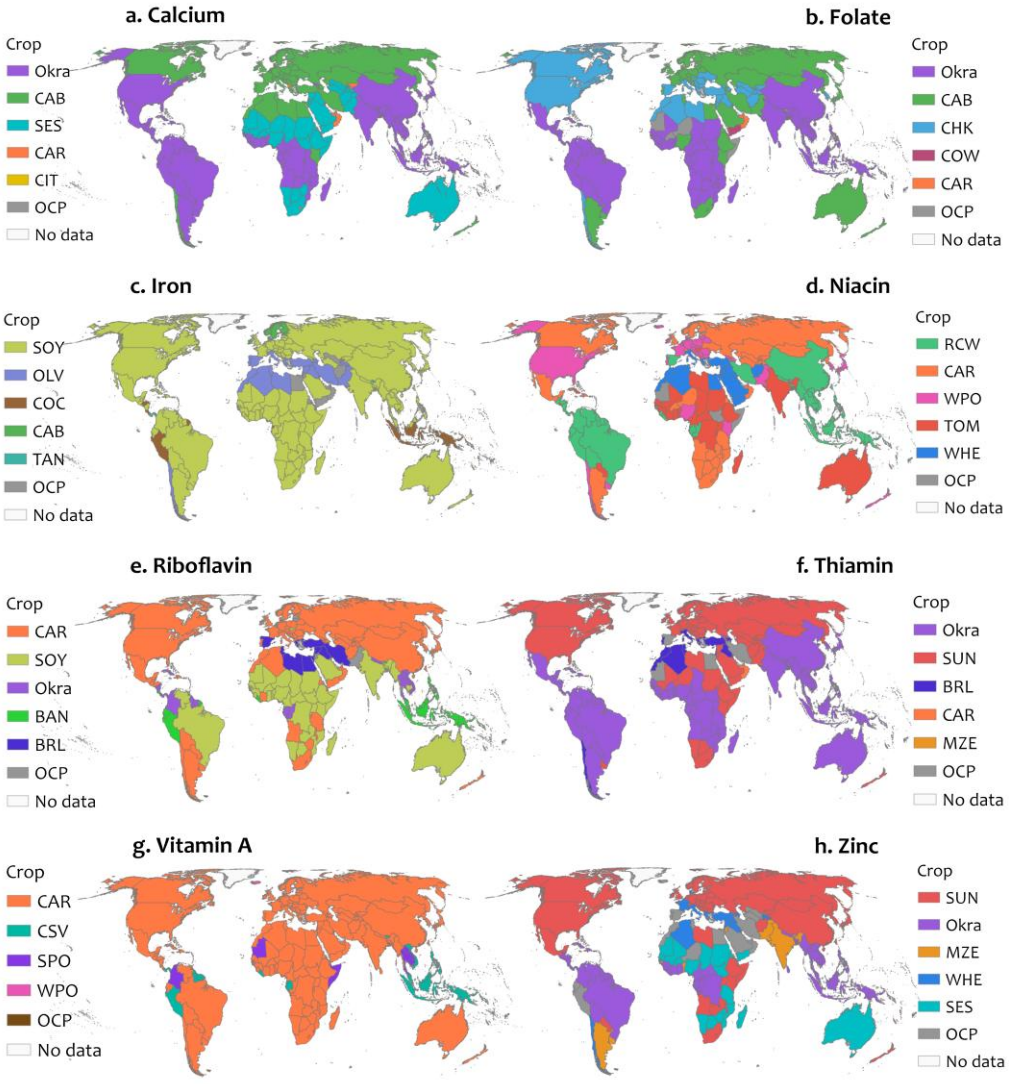

Fig. 2 | Geographic distribution of reference first-ranked crops for selected micronutrients. Maps show the first-ranked crop within each country–nutrient combination based on requirement-equivalent nutrient output per hectare. Panels show **a,** calcium; **b**, folate; **c,** iron; **d**, niacin; **e**, riboflavin; **f**, thiamin; **g**, vitamin **A**; and **h**, zinc. Crop colours identify the first-ranked crop and are consistent across panels where the same crop occurs. Codes denote **BAN**, banana; **BRL**, barley; **CAB**, cabbage; **CAR**, carrot; **CHK**, chickpea; **CIT**, citrus; **COC**, cocoa; **COW**, cowpea; **CSV**, cassava; **MZE**, maize; **OLV**, olive; **RCW**, wetland rice; **SES**, sesame; **SOY**, soybean; **SPO**, sweet potato; **SUN**, sunflower; **TAN**, tannia; **TOM**, tomato; **WHE**, wheat; and **WPO**, white potato. **OCP** denotes other crop options grouped for readability. Corresponding maps for the remaining five nutrients are shown in Extended Data Fig. 1. Full country–nutrient results, including the first-ranked crop, PII-weighted output metric and nutrient-specific low, moderate and high classes for all 13 nutrients, are provided in Supplementary Data 4. Low, moderate and high classes are defined relative to each nutrient and are not displayed in this figure.

1.3. **Production-value comparison narrowed high-ranking crop options**

Production value could be estimated for 7,747 of the 13,754 high-ranking observations, covering 24 crops across 177 national crop portfolios (Fig. 3a). The matched crops represented a median 69% of mapped harvested area within countries and 74.8% globally. Among classified observations, 3,934 had higher estimated production value than the current crop-portfolio benchmark, 956 were comparable, 1,114 had a moderate penalty and 1,743 had a high penalty (Fig. 3b). The remaining 6,007 observations were not compared because the crop was outside the matched production-value dataset or no valid country benchmark was available.

Production-value outcomes differed substantially among crop–nutrient combinations (Fig. 3c). Tomato showed the clearest higher or comparable profile: tomato–vitamin A, tomato–vitamin C and tomato–niacin accounted for 170, 169 and 148 higher or comparable observations, respectively, with no high-penalty observations. Sweet potato–vitamin A and citrus–vitamin C had 139 and 129 higher or comparable observations. In contrast, sunflower–thiamin and soybean–iron each had 91 high-penalty observations, followed by sunflower–copper, sunflower–zinc, sunflower–phosphorus and soybean–riboflavin. Not-compared observations were concentrated among crops without matched economic data, particularly carrot, okra and cabbage; carrot–vitamin A, carrot–riboflavin and carrot–calcium accounted for 207, 190 and 187 such observations.

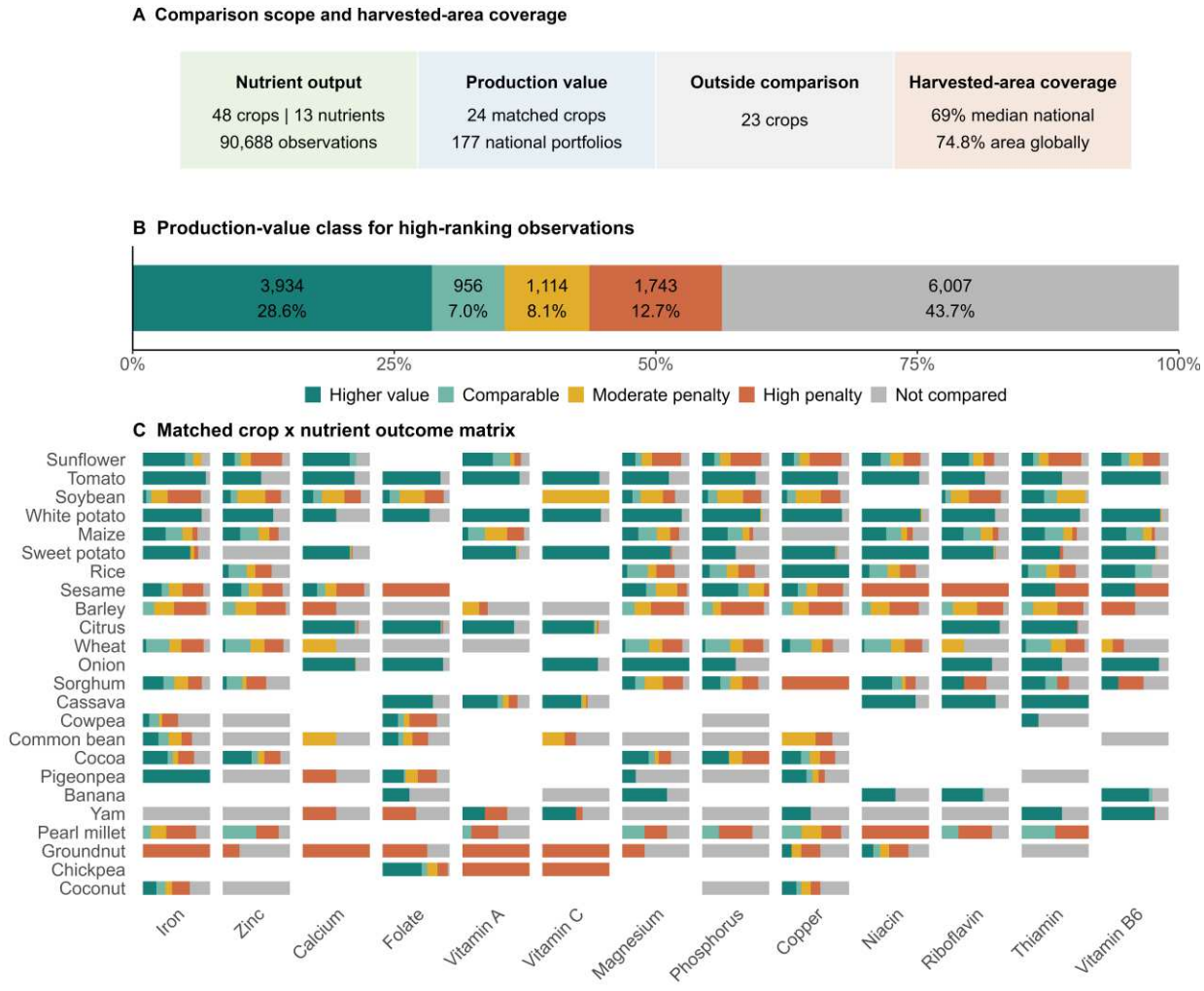

Fig. 3 | Production-value comparison of high-ranking crop–nutrient observations. a, Scope of the comparison, including the full nutrient-output set, crops included in and outside the production-value comparison, and harvested-area coverage of the matched crop portfolio. **b,** Distribution of high-ranking observations across production-value classes. The production-value ratio was calculated as candidate-crop production value divided by the current crop-portfolio benchmark, both in US$ ha^{-1}, and classified as higher value (≥1), comparable (0.75–<1), moderate penalty (0.50–<0.75) or high penalty (<0.50). Not compared denotes observations for which the crop was outside the matched harvested-area, yield and price dataset or no valid portfolio benchmark was available. **c**, Matched crop × nutrient matrix showing the distribution of high-ranking observations across the classes in **b**. Bar length is proportional to the number of country-level observations for each crop–nutrient pair; blank cells indicate that the crop–nutrient pair did not occur in the high-ranking set. Segment colours follow **b**. Crops outside the production-value comparison are excluded from c. Underlying data are provided in Supplementary Data 5.

1.4. **Countries and subregions differed in production-value outcomes**

Country-level profiles also varied markedly (Fig. 4). Twenty-four countries had at least 70% of high-ranking observations in the higher value, comparable or moderate-penalty range. Mauritania and Niger had the largest counts, with 55 of 65 observations each, followed by Bulgaria, Chad, Mali, Senegal and Sudan with 51 of 65 each, and Croatia with 50 of 65. Twenty-nine countries had at least 30% of high-ranking observations classified as high penalty, led by Djibouti with 43 of 65. A further 37 countries or territories had all high-ranking observations outside the production-value comparison.

At subregional scale (Extended Data Fig. 3), West Africa had the largest number of observations in the higher value, comparable or moderate-penalty range, with 604 of 1,040. Eastern Europe had the highest share in this range (437 of 650; 67%), followed by South Asia (329 of 520; 63%), Australia and New Zealand (81 of 130; 62%), Southern Africa (307 of 520; 59%) and West Africa (58%). High-penalty shares were largest in Melanesia (91 of 325; 28%), Southern Europe (181 of 845; 21%), Central Africa (121 of 585; 21%) and Western Asia (194 of 1,001; 19%). Not-compared observations followed a different geography: all 260 observations in both Micronesia and Polynesia were not compared, with similarly high shares in the Caribbean (1,000 of 1,625; 61%), North America (110 of 195; 56%), Northern Europe (407 of 793; 51%) and Eastern Asia (265 of 520; 51%). Globally, 4,453 high-ranking observations were not compared because the crop was outside the matched dataset and 1,554 because the country lacked a valid economic benchmark.

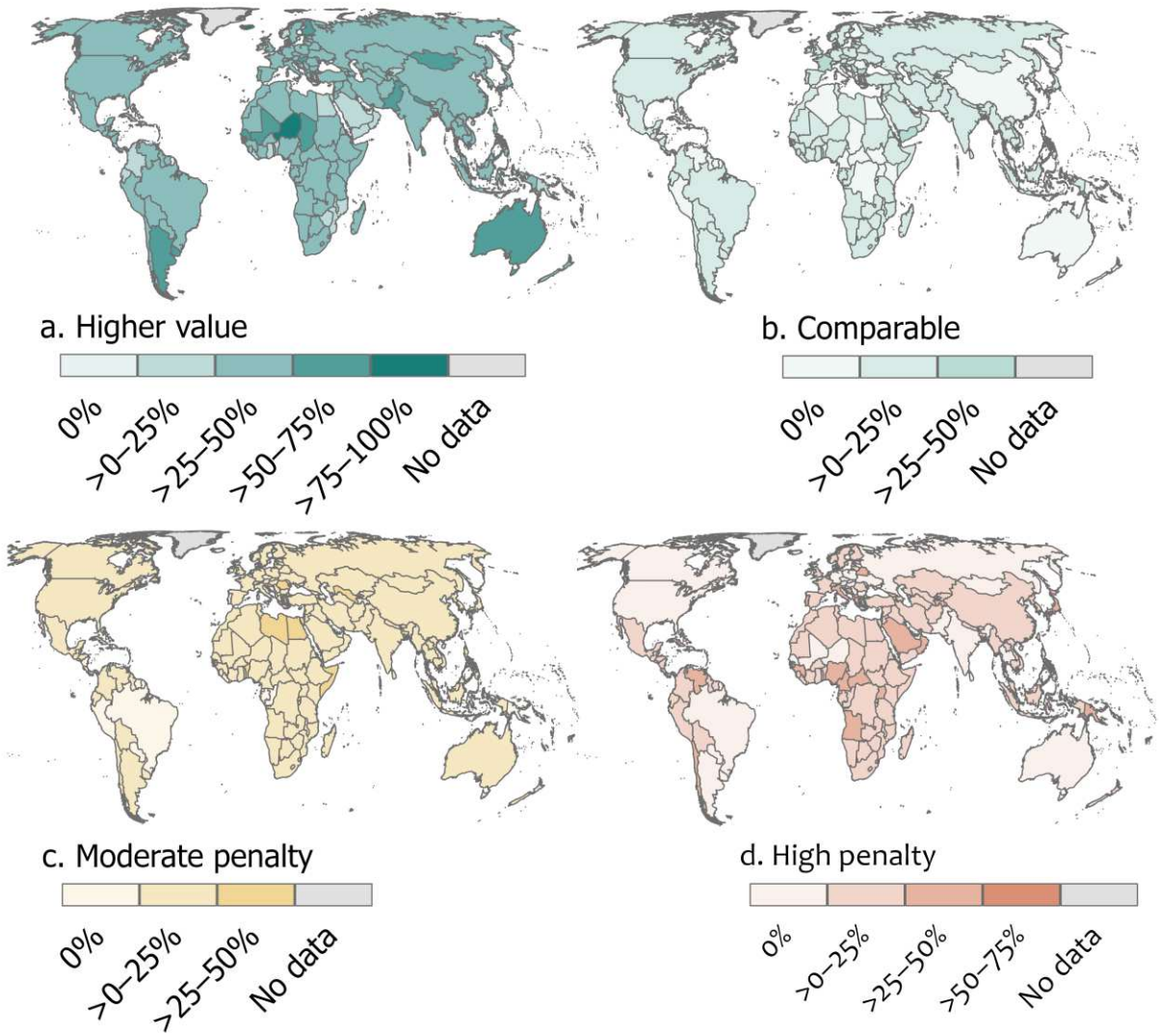

Fig. 4 | Country-level distribution of production-value classes. Maps show the share of each country's high-ranking crop–nutrient observations classified as **a,** higher value; **b,** comparable; **c,** moderate penalty; or **d**, high penalty. High-ranking observations were country–crop–nutrient combinations ranked within the top five by requirement-equivalent nutrient output per hectare. Production-value classes were based on the ratio of candidate-crop production value to the current crop-portfolio benchmark, both in US$ ha^{-1}: higher value, ≥1; comparable, 0.75–<1; moderate penalty, 0.50–<0.75; and high penalty, <0.50. Map categories indicate the percentage of each country's high-ranking observations in the corresponding class: 0%, >0–25%, >25–50%, >50–75% and >75–100%. A value of 0% indicates that the country was evaluated but had no observations in that class; no data indicates that no country-level value was available for mapping. Observations outside the matched harvested-area, yield and price dataset, or without a valid crop-portfolio benchmark, were classified as not compared and are not displayed as a separate panel. Full country-level outcomes are provided in Supplementary Data 6.

1.5. **Robustness analyses distinguished stable high-ranking combinations from rank-sensitive crop identities**

Spatial-support and producer-price sensitivities preserved the main structure of the results. Under the strictest spatial-support diagnostic, 2,600 of 2,769 country–nutrient sets retained at least one eligible crop and 2,487 of these (95.7%) retained the reference first-ranked crop. Among 2,587 sets with at least five eligible crops, 2,431 (94.0%) retained at least four of the reference top five and 2,162 (83.6%) retained all five (Fig. 5a).

The external yield benchmark showed moderate overall agreement between GAEZ and GYGA, with crop-specific differences in magnitude and geographic ordering (Fig. 6; Supplementary Data 8). Across 189 higher-support country–crop comparisons, Spearman ρ was 0.638 and Pearson r was 0.575. The median GAEZ-to-GYGA ratio was 0.631; 30.2% of estimates were within 25% and 66.1% within 50% of GYGA. Geographic agreement was strongest for wheat (ρ = 0.761; median ratio 0.680; 75.8% within 50%). Maize had a weaker rank correlation (ρ = 0.268) but a median ratio of 0.696 and 77.9% within 50%. Dryland and wetland rice had median ratios of 0.391 and 0.393, with 21.7% and 43.5% of estimates, respectively, within 50% of GYGA.

Annual producer-price scenarios produced similar aggregate distributions (Fig. 5b). Of 7,747 screened observations, 5,052 (65.2%) remained in the same class across all five years and 6,763 (87.3%) matched the five-year-median class in at least three years. The number classified as higher value, comparable or moderate penalty ranged from 5,994 to 6,176, compared with 6,004 in the median-price analysis. In the observed-price-only sensitivity, 3,686 of 3,852 observations (95.7%) retained the same class.

Composition-profile choice had a larger effect on exact crop order than on broader high-ranking membership (Fig. 5c). Across 1,000 baseline-inclusive simulations, the reference first-ranked crop was retained in 58.8% of country–nutrient sets on average, 74.0% of individual top-five memberships were retained, and at least four of five reference crops were retained in 62.7% of complete sets. Carrot for vitamin A, okra for calcium and magnesium, sunflower for phosphorus and okra for folate were among the most persistent first-ranked combinations. Some rank-sensitive crops nevertheless remained consistently represented in the top five; sunflower remained in the zinc top five in a median of 175 countries compared with 177 in the reference analysis, and citrus remained in the vitamin C top five in 160 compared with 163. Overall, recurrent high-ranking membership was more stable than exact first-ranked crop identity.

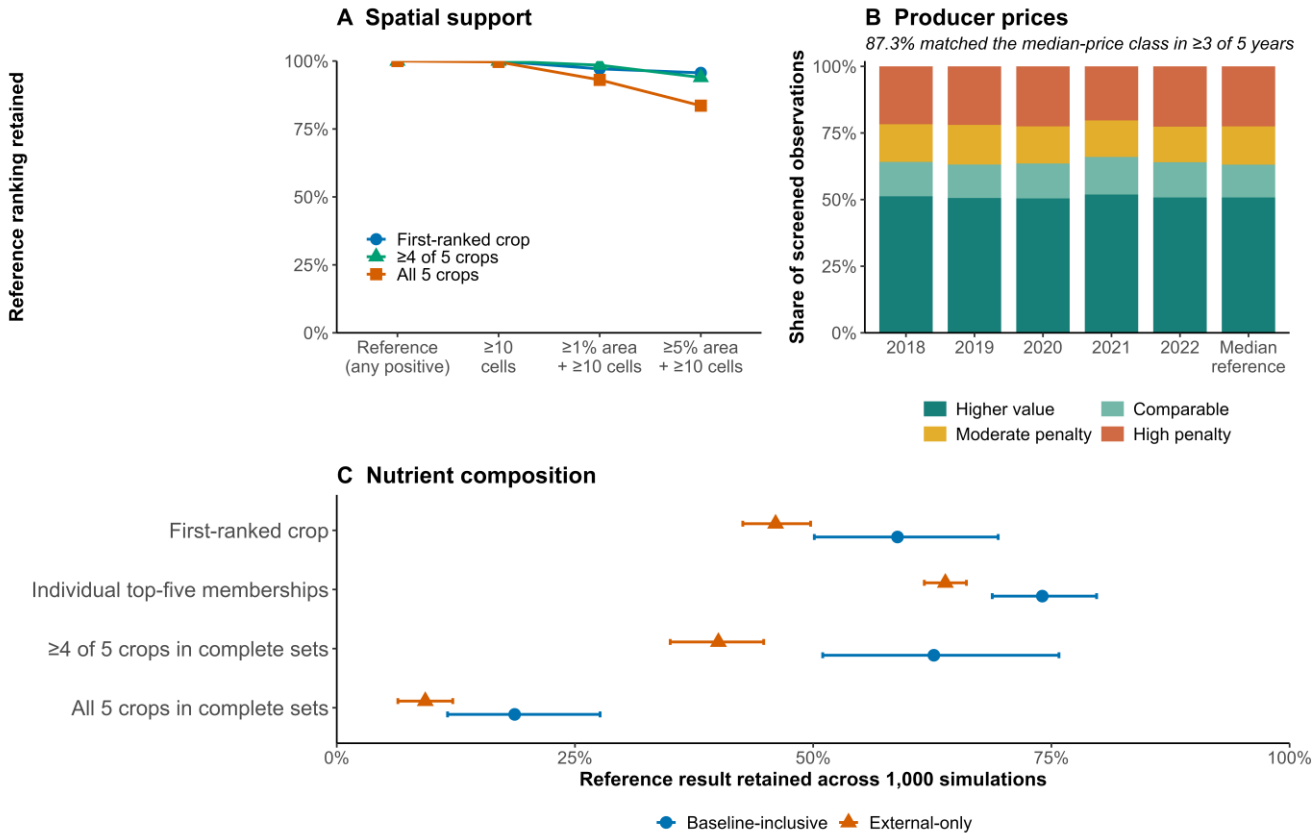

Fig. 5 | Robustness of crop-ranking and production-value conclusions to spatial support, producer-price variation and nutrient-composition profiles. a, Sensitivity of crop rankings to progressively stricter spatial-support filters applied to the GAEZ attainable-yield extraction. Points show retention of the reference first-ranked crop, at least four of five reference top-ranked crops, and all five reference top-ranked crops relative to the analysis retaining any positive attainable-yield support. **b,** Production-value class distributions obtained by rebuilding the producer-price analysis separately for each year from 2018 to 2022, compared with the reference analysis based on median 2018–2022 prices. **c,** Sensitivity of crop rankings to alternative coherent nutrient-composition profiles across 1,000 Monte Carlo simulations. Points show mean retention of the reference result and horizontal intervals show the 5th–95th simulation percentiles for the baseline-inclusive and external-only scenarios. Simulation percentile ranges describe sensitivity to composition-profile choice and are not statistical confidence intervals. Full robustness summaries and audit outputs are provided in Supplementary Data 7.

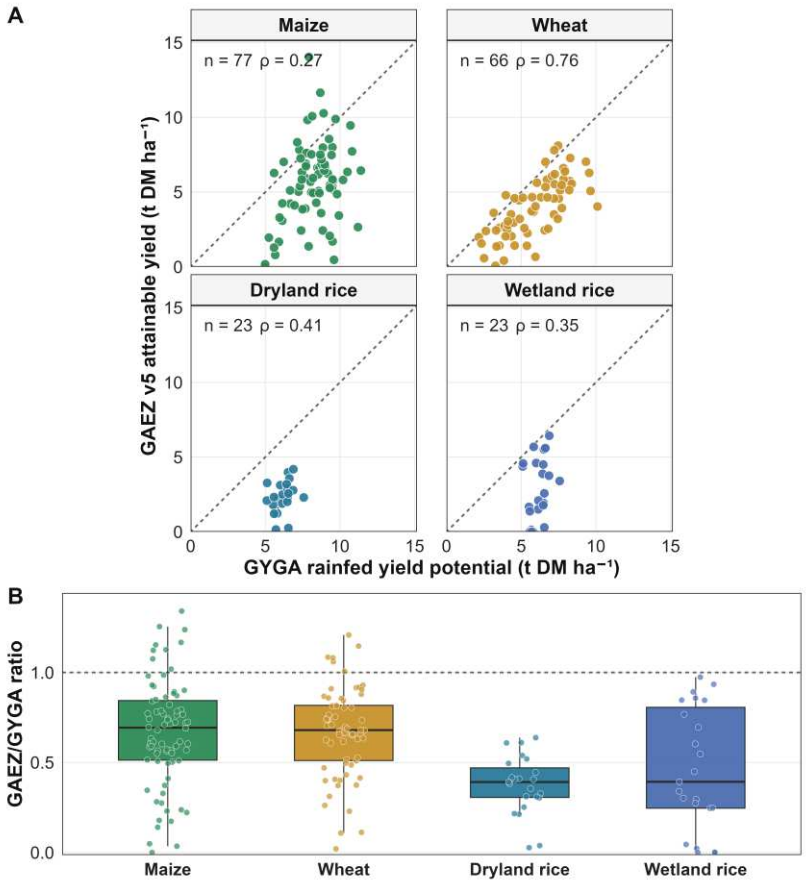

Fig. 6 | External benchmark of GAEZ v5 attainable yields against GYGA rainfed yield potential. a, Country-level GAEZ v5 rain-fed high-input attainable yields compared with Global Yield Gap Atlas (GYGA) rainfed water-limited yield-potential estimates for maize, wheat and rice. GAEZ and GYGA yields were restricted to common valid spatial support and aggregated using MapSPAM 2020 v2r2 rainfed harvested area as a weighting layer. GYGA yields were converted from standard commercial moisture content to dry-matter equivalents before comparison. Dryland and wetland rice were retained as separate GAEZ variants and independently compared with the GYGA rainfed-rice surface. Points represent higher-support country comparisons, defined as at least three common MapSPAM cells and at least 50% representation of mapped rainfed harvested area. Values within panels give the number of country comparisons (n) and Spearman rank correlation (ρ). The dashed diagonal denotes 1:1 agreement. b, Distribution of GAEZ-to-GYGA yield ratios across the same higher-support country comparisons. Points represent individual country comparisons, boxes show the interquartile range with the median indicated by the horizontal line, and whiskers extend to the most extreme values within 1.5 times the interquartile range. The dashed horizontal line denotes a ratio of 1, corresponding to equal GAEZ and GYGA yield estimates. Underlying country-level comparisons and summary statistics are provided in Supplementary Data 8.

2. **Discussion**

Global micronutrient gaps persist despite long-term growth in food production [1,3,5,17], highlighting that agricultural output alone does not ensure nutritionally adequate food systems. Crop production nevertheless remains an important upstream pathway through which agriculture shapes nutrient availability [11,18,19]. By linking attainable yield, crop nutrient composition and human requirements across 213 countries and territories, 48 food crops and 13 micronutrients, the present analysis identifies crop–nutrient opportunities that are specific to nutrient and place, and shows that high attainable nutrient output does not consistently align with current monetary production-value conditions (Figs. 1–4; Extended Data Figs. 2 and 3; Supplementary Data 2–6).

These findings extend evidence that aggregate production can conceal nutrient-specific shortfalls [5,17] and that crop diversity is nutritionally meaningful only where additional crops contribute nutrients that are limiting within a food system [7,20–22]. Previous work on edible plant diversity, neglected and underutilised crops and opportunity crops has highlighted the potential of legumes, millets, roots, tubers, vegetables and other locally adapted crops, while also identifying constraints related to crop improvement, seed systems, markets and nutrient-composition data [10,23–30]. The present results complement this literature by showing that nutrient-relevant crop options emerge from the interaction of nutrient composition, attainable yield, population requirements and geography rather than from crop identity alone. They also show that common commercial crops can be important. Tomato, carrot and white potato, for example, were prominent in the nutrient-ranking analysis despite receiving less attention in much of the underutilised-crop literature [22,26–31], while soybean, okra and sweet potato overlapped more closely with previously identified opportunity crops. These patterns support evaluating both established and underutilised crops against nutrient-specific production potential rather than assuming that either group is inherently preferable.

Robustness analyses distinguished recurrent high-ranking crop–nutrient combinations from invariant rank positions. Spatial-support filtering and annual producer-price scenarios preserved the main structural patterns, whereas nutrient-composition profiles had greater effects on exact first-ranked identities than on broader top-five membership (Fig. 5; Supplementary Data 7). Consequently, greater confidence can be placed in crop–nutrient combinations that recur among the highest-ranking options across alternative assumptions than in a single crop occupying the first

position under all composition profiles. The external benchmark added a complementary source of uncertainty: GAEZ and GYGA showed moderate overall agreement in geographic ordering across overlapping cereals, but absolute yield magnitudes differed materially and in a crop-dependent manner, particularly for rice (Fig. 6; Supplementary Data 8). Thus, robustness of the comparative crop-opportunity framework should be distinguished from precision of the attainable-yield estimates on which absolute output magnitudes depend.

The production-value comparison further shows that nutrient productivity and monetary production value are not interchangeable objectives [15]. Many high-ranking crop options were estimated to have production values close to or above current national crop-portfolio benchmarks, whereas others were associated with substantial penalties or could not be compared because harmonised economic data were unavailable. These classes provide economic context rather than evidence of profitability or adoption. Unlike diet-affordability analyses, which evaluate whether nutritionally adequate diets are financially accessible to consumers [4,32,33] , the present comparison asks whether high-ranking crop options have estimated gross production values per hectare that are higher than, similar to or lower than current crop-portfolio benchmarks. Geographic differences in these outcomes therefore reflect the relative position of candidate crops within each national portfolio rather than the absolute value of the portfolio itself. Variation in data coverage across countries further constrains such comparisons [34,35].

The analysis should therefore be interpreted as a global screening framework rather than as a basis for direct crop recommendations. First, attainable-yield estimates remain dependent on the modelling framework (Fig. 6). Comparisons between top-down frameworks such as GAEZ and bottom-up GYGA estimates have previously shown substantial disagreement, particularly at finer spatial scales [36]. The benchmark undertaken here similarly showed that GAEZ and GYGA retained some common geographic structure but differed in yield magnitude. GYGA gridded estimates are themselves modelled extrapolations from site-specific yield-potential estimates and should not be treated as ground truth [37]. GAEZ is therefore used as a globally consistent comparative layer rather than as a precise prediction of locally attainable or realised yield. Country-level aggregation also masks subnational variation in soils, climate, infrastructure, land access, markets and farming systems [14,34,35], so locally calibrated agronomic assessment would be required before production recommendations could be made.

Second, prevalence of inadequate intake is a population-level contextual indicator rather than a measure of individual dietary exposure. The estimates used here were derived from national food-supply availability, nutrient composition and population requirements [38] and may conceal inequalities in access and consumption within countries. PII-weighted results therefore indicate where attainable nutrient output overlaps with greater estimated inadequacy, not where additional crop production would necessarily improve individual intake or reduce deficiency. Crop nutrient output likewise cannot be equated with realised dietary intake. Nutrient concentrations vary with genotype, environment, management, storage, processing and cooking [39], while dietary contribution depends on edible form, processing pathways, affordability, preferences and intra-household allocation [16,18]. The composition sensitivity analysis partly captures this uncertainty but cannot represent the full pathway from production to consumption (Fig. 5c).

Third, the production-value comparison is not a profitability or adoption analysis (Figs. 3 and 4; Extended Data Fig. 3). Estimated gross value per hectare does not incorporate production costs, labour, capital requirements, input access, price volatility, credit, land tenure, market reliability or farmer preferences [40,41]. The production-value classes should therefore be interpreted as relative screening categories rather than validated economic decision thresholds. Interpretation is also limited by the availability of harmonised MapSPAM harvested area, GAEZ attainable yield and FAOSTAT producer-price data. Crops or countries without the required matched information were retained as not compared rather than being interpreted as low-value cases.

Finally, the analysis represents crop production under current attainable-yield conditions. It does not incorporate livestock-derived foods, allocation of crops to animal feed or future climate-driven changes in suitability and productivity. These dimensions could alter the relative opportunities identified here and warrant integration in future food-system assessments.

Taken together, the framework links feasible crop production with human nutrient requirements while avoiding the assumption that crop choice alone can resolve micronutrient inadequacy. It identifies recurrent high-ranking crop–nutrient combinations (Figs. 1 and 2; Extended Data Fig. 2), places them against current monetary production-value conditions (Figs. 3 and 4; Extended Data Fig. 3), tests their robustness to major analytical assumptions and independently benchmarks the attainable-yield layer against an external yield-potential framework (Figs. 5 and 6). Used alongside local evidence on diets, production costs, markets, seed systems, labour and institutions,

this approach can narrow broad cropland potential to crop–nutrient combinations warranting context-specific agronomic, economic and dietary assessment.

3. **Methods**

3.1. **Study design and analytical overview**

Country–crop–nutrient observations were used to assess attainable crop-derived micronutrient output relative to human requirements and to place this output within country-level population-need and production-value contexts. The analysis proceeded in two stages. First, attainable yield, nutrient composition and human nutrient requirements were combined across 48 food crops to calculate requirement-equivalent nutrient output per hectare. Crops were ranked within each country–nutrient combination using this metric, while prevalence of inadequate intake (PII) was incorporated as a need-context layer to indicate where nutrient-output potential coincided with greater estimated population inadequacy. Second, high-ranking crop options with matched harvested-area, attainable-yield and producer-price data were compared with the harvested-area-weighted production-value benchmark of the current crop portfolio. Production value was expressed in US$ ha^{-1}.

The primary unit of analysis was the country–crop–nutrient observation. Country-level outputs retained country name, three-letter country code and detailed UN Geoscheme subregion. The three-letter country code was used as the primary key for linking source datasets and analytical outputs.

3.2. **Crop set and analytical scope**

The nutrient analysis included 48 food crops with nutrient-composition data that could be matched to attainable-yield layers (Supplementary Table 1). Non-food crops and crop categories without a match between composition data and yield layers were excluded. The analysis covered 13 micronutrients with corresponding requirement and inadequacy data: iron, zinc, calcium, folate, vitamin A, vitamin B_6, vitamin C, magnesium, phosphorus, copper, niacin, riboflavin and thiamine.

The production-value comparison used a narrower crop set because it required consistent matches across harvested area, attainable yield and producer-price data. This comparison included 24 crops across 177 countries. The difference between the 48-crop nutrient analysis and the 24-crop production-value comparison was retained in interpretation: missing production-value results indicate data or benchmark limits, not evidence of low production value.

3.3. **Attainable yield data and unit harmonisation**

Crop yield potential was derived from Global Agro-Ecological Zones (GAEZ v5) raster layers representing "Average attainable yield of current cropland (Kg (DW)/ha)" [14]. These layers provide modelled crop-specific attainable yields on the GAEZ current-cropland domain under the historical 2001–2020 climate baseline. The analysis used attainable yield rather than suitability classes, as nutrient-output calculations require yield magnitudes. Reported yields were not used, as they also reflect realised management, input access, markets and institutions. The native 30-arc-second rasters, approximately 1 km at the equator, were aggregated to country polygons. Country-level crop yield estimates were calculated from cells with positive yield values. Non-positive, missing, infinite or invalid values were excluded from yield summaries. Country–crop combinations without positive attainable-yield values were excluded from crop rankings rather than assigned zero nutrient output.

Because GAEZ v5 yields are reported in kilograms of dry weight per hectare, whereas food-composition data and FAOSTAT producer prices are expressed on a product- or fresh-weight basis, dry-weight yield was retained for audit. Product-equivalent yield was used for nutrient-output and production-value calculations and was calculated using crop-specific dry-matter fractions from the USDA composition data. For the nutrient-output analysis, dryland and wetland rice were retained as distinct GAEZ crop options, allowing their attainable-yield differences to be represented directly in the crop rankings. Rice harmonisation required for the production-value comparison was handled separately during economic-data matching and did not alter the nutrient-ranking results. In main figures, rice is labelled as "Rice"; the dryland and wetland components are individually documented in Supplementary Information.

3.4. **Crop nutrient composition and nutrient output**

Crop nutrient-composition data were obtained primarily from USDA FoodData Central [42], with missing crop profiles supplemented from published food-composition literature where required, including pearl [43], foxtail [44] and finger millet [45] (Supplementary Data 1). Nutrient values were expressed per 100 g edible product. Water content was retained to calculate dry-matter fractions for converting GAEZ dry-weight yield to product-equivalent yield. For each country–crop–nutrient observation, annual nutrient output per hectare was calculated from product-equivalent yield and nutrient content per 100 g edible product. Daily nutrient output was calculated by dividing annual output by 365. Both annual and daily outputs were retained in the data.

Nutrient output was compared with Harmonized Average Requirements (HARs) for adult women aged 25 to 50 years [46]. HARs were linked by nutrient and used as a common benchmark for comparing crop-derived nutrient output across countries, crops and nutrients. Country-specific need was introduced separately through prevalence of inadequate intake. For iron, the low-bioavailability HAR was used; for zinc, the unrefined-diet HAR was used. The main per-hectare metric expressed how many annual benchmark requirements could be supplied by one hectare of crop production. This is a modelled output measure. It does not represent observed intake, dietary adequacy, bioavailability-adjusted consumption or the number of people actually fed.

3.5. **Prevalence of inadequate intake weighting and crop ranking**

To prioritise crop nutrient opportunities by nutritional need, the above nutrient output was weighted by country–nutrient prevalence of inadequate intake (PII) [38]. PII values were linked by ISO3 code and nutrient for the 13 micronutrients with aligned requirement, composition and prevalence data. Vitamin B_{12} was excluded because the analysis was restricted to plant-derived crop pathways. Missing country–nutrient PII values were filled using nutrient-specific medians in a fixed sequence: UN subregion, broader region and global. A subregional or regional median was used when one or more observed values were available at that geographic level; otherwise, the next level was used. Observed and imputed PII values were flagged in the output data.

For each country–crop–nutrient observation, the PII-weighted score was calculated by multiplying annual benchmark requirements supplied per hectare by the corresponding country–nutrient PII value. Because PII is constant across crops within a given country–nutrient combination, this weighting changes the magnitude of the score but does not change the crop order within that country–nutrient set. Crops were therefore ranked within each country and nutrient using requirement-equivalent nutrient output per hectare, with the corresponding PII-weighted score retained to indicate alignment between attainable nutrient output and country-level prevalence of inadequate intake. The high-ranking set comprised crops ranked in the top five for each country and nutrient. This top-five set, together with the associated PII-weighted scores, was used to summarise crop breadth, country-level patterns, subregional patterns and the production-value comparison.

3.6. **Diagnostic comparison of crop rankings**

To examine why crop–nutrient combinations appeared in the high-ranking set, four diagnostic quantities were compared for each crop and nutrient: dry-weight-adjusted nutrient density, median GAEZ dry-weight yield, unweighted annual benchmark requirements supplied per hectare, and the PII-weighted score. Within each country–nutrient combination, crop order was determined by requirement-equivalent nutrient output per hectare. Because PII is constant across crops within a given country–nutrient combination, PII weighting changes the magnitude of the score but does not change the within-country crop order for that nutrient.

Rank-shift diagnostics were therefore calculated at the crop–nutrient summary level within each nutrient, where PII varies across countries. For each nutrient, crop–nutrient combinations were ranked using the unweighted output summary and the PII-weighted score summary. Rank shifts after PII weighting were calculated as the unweighted rank minus the PII-weighted rank. Positive values indicate that a crop–nutrient combination ranked higher after accounting for the geographic distribution of population inadequacy.

Top-ranked crop–nutrient combinations were then assigned to diagnostic groups used in Fig. 1. “Composition” denotes cases with high nutrient density but lower yield ranking. “Yield” denotes cases with high yield ranking but more moderate nutrient density. “Composition + yield” denotes

cases ranking strongly for both. “Stable high output” denotes cases that ranked strongly before and after PII weighting. “Need alignment” denotes cases that ranked higher after accounting for the geographic distribution of population inadequacy. Remaining cases were classified as mixed. These groups were used to describe ranking patterns and should not be interpreted as causal explanations.

3.7. **Harvested-area data and crop-share**

Current crop portfolios were represented using the Spatial Production Allocation Model (MapSPAM V2r2) 2020 harvested-area layer [47]. MapSPAM provides gridded harvested-area estimates for crop categories at 10 × 10 km resolution and covers more than 90% of global crop area across 46 crops and crop groups. It uses circa-2020 input data and 2019–2021 averages for harvested area, yield and production. MapSPAM was therefore used to represent current crop-portfolio structure, rather than FAOSTAT harvested-area tables, which provide national statistical totals but not a gridded crop allocation layer, or GAEZ, which was used here to represent attainable yield potential rather than realised cropping patterns.

Harvested area was summed by ISO3 code and crop across all grid cells. Grid-cell rows were not averaged. Total harvested area across all MapSPAM crop categories was retained to show how much of each country’s mapped crop area was represented in the production-value comparison. Crop shares for the production-value benchmark were then calculated only for the 24 crops with matching harvested-area, attainable-yield and producer-price data. For each country, the harvested area of each matched crop was divided by the total harvested area of all matched crops in that country:

$$s_{c,k} = \frac{A_{c,k}}{\sum_{j \in K_c} A_{c,j}}$$

where $s_{c,k}$ is the harvested-area share of crop k in country c, $A_{c,k}$ is the MapSPAM harvested area for crop k, and K_c is the set of matched crops included in the production-value benchmark for country c.

Coverage of the production-value comparison was calculated as:

$$Coverage_c = \frac{\sum_{j \in K_c} A_{c,j}}{A_c^{MapSPAM}}$$

where $A_c^{MapSPAM}$ is the total harvested area across all MapSPAM crop categories in country c. This coverage metric was used to distinguish countries where the production-value benchmark represented a larger share of mapped current crop production from countries where interpretation was more limited by crop coverage.

3.8. **FAOSTAT producer-price harmonisation**

Producer prices were taken from FAOSTAT for 2018–2022 [48]. This five-year window aligned the price data with the circa-2020 MapSPAM and GAEZ baseline while reducing the influence of any single reporting year. Prices were expressed in US$ t^{-1}. For each country and crop, the main price value was the median of available annual producer prices over the five-year window. The arithmetic mean was retained as a sensitivity value and used to check cases where short-term price variation made the mean and median diverge. FAOSTAT crop items were matched to the 24 crops included in the production-value comparison. Country names were converted to ISO3 codes and aligned with the MapSPAM–GAEZ country list.

Missing country–crop prices were not set to zero. Instead, missing prices were filled using crop-specific medians in a fixed sequence: country, UN subregion, broader region and global. A subregional or regional median was used when at least one observed crop price was available at that geographic level; otherwise, the next level was used. All final prices retained a source flag, distinguishing observed country prices from values filled using subregional, regional or global crop-specific medians.

3.9. **Production-value comparison**

The production-value comparison estimated how each high-ranking crop option compared with the current crop portfolio in the same country. Production value was expressed in US$ ha^{-1} and calculated from product-equivalent attainable yield and FAOSTAT producer price. This comparison was not a profitability, adoption, market-access, welfare or full opportunity-cost

analysis, because it did not include production costs, labour, input constraints, price risk, policy incentives or market conditions.

For each country and crop, estimated production value was calculated as:

$$PV_{\{c,k\}} = Y_{\{c,k\}}^{\{product\}} \times P_{\{c,k\}}$$

Where $PV_{\{c,k\}}$ is the estimated production value of crop (k) in country (c), $Y_{\{c,k\}}^{\{product\}}$ is product-equivalent attainable yield in tonnes per hectare, and $P_{\{c,k\}}$ is the harmonised FAOSTAT producer price in US$ t^{-1}.

The current crop-portfolio benchmark was calculated as the harvested-area-weighted mean production value of the matched crops in each country:

$$PV_c^{portfolio} = \sum_{j \in K_c} s_{c,j} PV_{c,j}$$

where $PV_c^{\{portfolio\}}$ is the current crop-portfolio benchmark in country (c), $s_{\{c,j\}}$ is the MapSPAM harvested-area share of crop (j), and K_c is the set of matched crops included in the production-value benchmark for that country.

Each crop option was then compared with the country benchmark using the ratio:

$$R_{c,k} = \frac{PV_{c,k}}{PV_c^{portfolio}}$$

where $R_{\{c,k\}}$ is the production-value ratio. Values above 1 indicate higher estimated production value of the candidate crop than the current crop-portfolio benchmark, while values below 1 indicate lower estimated production value. For descriptive comparison, production-value ratios were grouped using pre-specified thresholds: at or above the portfolio benchmark (≥1.00), within 25% below the benchmark (0.75–<1.00; comparable), more than 25% and up to 50% below the benchmark (0.50–<0.75; moderate penalty), and more than 50% below the benchmark (<0.50;

high penalty). The 0.75 and 0.50 thresholds correspond to candidate production values that are approximately 25% and 50% below the benchmark, respectively, and were selected with reference to FAO agricultural suitability approaches that use losses of this magnitude to distinguish moderate and severe production constraints [49].

These thresholds represent simple proportional departures from the benchmark and were used as ordinal screening categories rather than as externally validated economic decision thresholds. Because production value was calculated from attainable yield and price without accounting for production, labour, capital, marketing or other costs, the resulting ratios represent relative gross output value rather than profitability or net returns [50]. Country–crop observations with missing attainable yield or price, or with a non-positive portfolio benchmark, were not assigned a production-value class because the ratio could not be estimated or meaningfully interpreted; these observations were retained as "not compared".

3.10. **Joining nutrient rankings and production-value classes**

The nutrient ranking and production-value comparison were joined by ISO3 code and crop. Because production value was calculated at country–crop level, the same production-value class was attached to each corresponding country–crop–nutrient observation. The production-value class was retained as a separate interpretive variable and was not included in the need-weighted nutrient score. High-ranking nutrient observations were defined as country–crop–nutrient observations ranked within the top five for a given country and nutrient using requirement-equivalent output per hectare. These observations were then described according to their production-value class: higher than the current crop-portfolio benchmark, comparable, moderate penalty, high penalty or not compared.

For summary tables, three alternative filters were retained. The broadest filter combined high-ranking nutrient observations with production-value classes of higher than benchmark, comparable or moderate penalty. A narrower filter retained only observations classified as higher than benchmark or comparable. A coverage-qualified filter retained observations in the broadest filter only where the matched crops represented a moderate or high share of mapped harvested area in the country. These filters were used for interpretation and sensitivity checks. High-ranking observations with a high production-value penalty were retained as a separate group. Observations

without a production-value class were retained as not compared. These cases indicate that the crop or country benchmark was unavailable in the matched harvested-area, yield and price data, not that the crop had low production value.

3.11. **Geographic summaries**

Country-level results were summarised using detailed UN Geoscheme subregions. These summaries were used to describe geographic patterns in high-ranking crop–nutrient observations, first-ranked crops and production-value outcomes. Detailed subregion labels were used rather than broad regional groupings. Missing, broad or non-standard labels were corrected where an ISO3-based assignment was available. Non-standard aggregate geographies were excluded from reported country and subregional summaries.

3.12. **Robustness analyses**

Robustness was assessed for four sources of analytical uncertainty: spatial support for attainable-yield estimates, the yield-potential framework, temporal variation in producer prices and alternative nutrient-composition profiles.

Spatial sensitivity was assessed by repeating the crop-ranking analysis under progressively stricter requirements for positive attainable-yield support. The reference analysis retained crops with any positive attainable-yield support. Alternative specifications required at least 10 positive-yield grid cells, at least 1% of the intersected raster area with positive attainable yield together with at least 10 positive-yield cells, or at least 5% positive-yield area together with at least 10 positive-yield cells. For each specification, crops were reranked within each country–nutrient combination using requirement-equivalent nutrient output per hectare. Stability was evaluated from retention of the reference first-ranked crop and the reference top-five crops. Comparisons of top-five membership were restricted to country–nutrient combinations in which at least five crops met the corresponding spatial-support requirement.

Uncertainty associated with the attainable-yield framework itself was assessed using an external benchmark against Global Yield Gap Atlas (GYGA) rainfed water-limited yield-potential

estimates for the overlapping cereal crops [51]. Rain-fed high-input GAEZ v5 estimates for maize, wheat, dryland rice and wetland rice were compared with high-resolution GYGA-based yield-potential surfaces for rainfed maize, wheat and rice. The GYGA surfaces integrate site-specific bottom-up yield-potential estimates with a spatial machine-learning metamodel and provide predictions at 30-arc-second resolution for areas within the modelled domain of applicability [37,51]. GAEZ and GYGA surfaces were restricted to common valid spatial support and aggregated to country level using MapSPAM 2020 v2r2 rainfed harvested area as a weighting layer. GYGA yields, reported at standard commercial moisture content, were converted to dry-matter equivalents before comparison. Dryland and wetland rice were retained as separate GAEZ variants and each compared independently with the GYGA rainfed-rice surface. Agreement was evaluated using Spearman and Pearson correlations, root-mean-square error, mean error, the median GAEZ-to-GYGA yield ratio and the proportions of country estimates within 25% and 50% of the GYGA benchmark. The primary higher-support comparison required at least three common MapSPAM cells and representation of at least 50% of mapped rainfed harvested area. This analysis was treated as an external benchmark of yield magnitude and geographic ordering for overlapping cereals and was not used to replace the GAEZ yield layer or rerank the full 48-crop analysis.

Sensitivity to producer-price variation was assessed by repeating the production-value analysis using annual FAOSTAT producer prices for each year from 2018 to 2022 in place of the median price for 2018–2022. The same price harmonisation, geographic imputation procedure, portfolio benchmark and production-value classification thresholds were applied in each annual analysis. Stability was evaluated from agreement between annual classifications and the five-year-median classification. A further sensitivity analysis was restricted to crop–country observations with directly observed producer prices to assess whether the use of geographically imputed prices affected the resulting production-value classifications.

Sensitivity to nutrient composition was assessed using 1,000 Monte Carlo simulations based on alternative coherent food-composition profiles. Alternative profiles were drawn from the Australian Food Composition Database [52] and the FAO/INFOODS Food Composition Table for Western Africa [53] and were evaluated alongside the reference profiles used in the main analysis [42]. Composition values were expressed on a dry-matter basis using reported water content to maintain consistency with GAEZ attainable yields expressed as dry weight. Whole composition profiles

were sampled jointly across the 13 nutrients rather than varying individual nutrients independently, thereby preserving the nutrient composition represented within each food profile. Crop variants sharing a common composition group were assigned the same sampled profile within each simulation.

Two composition scenarios were evaluated. In the primary baseline-inclusive scenario, the reference composition profile remained available alongside external alternative profiles. In the external-only scenario, the reference profile was excluded where external alternatives were available; composition groups without suitable external alternatives retained their reference profile. Sampling was balanced across composition sources by first selecting a source with equal probability and then selecting one available profile from that source. External alternatives were available for 41 of the 43 composition groups. For each simulation, requirement-equivalent nutrient output was recalculated, and crops were reranked within each country–nutrient combination. Robustness was summarised by retention of the reference first-ranked crop, retention of individual reference top-five memberships, and the proportion of complete top-five sets retaining at least four or all five reference crops. The 5th–95th percentiles across simulations describe variation associated with composition-profile choice and were not interpreted as statistical confidence intervals.

4. **Data availability**

All primary datasets used in this study are publicly available from the original data providers or cited sources, including agroecological attainable-yield data [14], external GYGA yield-potential data [51], crop nutrient-composition data [42,52,53], population nutrient requirements [46], prevalence of inadequate intake estimates [38], harvested-area data [47] and producer-price data [48]. Processed country-level outputs, figure-source data and supplementary datasets generated for this study will be deposited in a public repository. Repository accession details and persistent links will be provided before publication.

5. **Code availability**

All code used to process input data, harmonise crop and country identifiers, calculate nutrient-opportunity metrics, construct the production-value comparison and generate figures will be made

available in a public repository upon publication. Repository details and versioned release information will be provided in the final version of the manuscript.

6. **Author contributions**

E.A.A. conceived the study, developed the analytical framework, curated and harmonised the data, performed the analyses, generated the figures and wrote the first draft. N.W.S., W.C.M. and T.M.R.M. contributed to study design, interpretation of results and manuscript revision. All authors reviewed and approved the final manuscript.

7. **Competing interests**

The authors declare no competing interests.

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9. **Ethics declaration**

Not applicable.

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- SupplementaryData7Robustness.xlsx
- SupplementaryData3Diagnosticprofiles.xlsx
- SupplementaryData1Cropcompositionandrequirements.xlsx
- SupplementaryData4Countryandsubregionalnutrientopportunity.xlsx
- SupplementaryData6Countryandsubregionalproductionvalue.xlsx
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- SupplementaryData8ExternalGAEZv5GYGAyieldbenchmark.xlsx
- SupplementaryData2Referencetopfiverankingsandbreadth.xlsx
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