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Crop rotations synergize yield, nutrition, and revenue: a meta-analysis

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Increasing agricultural yields through crop diversification may help achieve food and nutrition security. However, the benefits of a transition from monoculture to crop rotation may be reduced if trade-offs exist between yields, dietary energy, nutrients, and revenue. Here, we synthesize 3663 paired field-trial yield observations (1980–2024) and show that globally, crop rotation increased subsequent crop yield, with legume pre-crops outperforming non-legume pre-crops (23% and 16% average increases, respectively). Considering the entire sequence (i.e., pre-crop plus main crop), rotations increased total yields, dietary energy, protein, iron, magnesium, zinc, and revenue by 14–27% relative to continuous monoculture. Notably, win-win relationships among yield, nutrition, and revenue were consistently higher (33–54%) than trade-offs. Different high-performing crop rotations have been identified for several major agricultural production regions worldwide. These findings establish crop rotations as a strategic pathway to enhance synergies among agricultural yields, nutrition, and revenue compared to monoculture, offering scalable solutions for sustainable intensification.

Eradicating hunger remains a critical challenge and a central focus of the Sustainable Development Goals (SDGs). Despite efforts to increase or sustain yields through crop diversification, countries in the Global North are contending with nutritionally "hidden hunger", while those in the Global South face both food insecurity and undernourishment[1–4]. In light of the anticipated global population and per capita income increases, and the resultant increased demand for food, replacing monoculture with crop rotation - an ecological intensification practice employed to increase crop diversity and improve crop yields, could be a pivotal strategy[5–7]. Recent evidence suggests that nearly 50% of the world is suitable for diversified farming[8], however, designing sustainable cropping sequences to achieve multiple goals remains a challenge[9]. At a national scale, diversity of total crop production is associated with improved health outcomes and stability of national food supply[10,11]. Crop rotation not only diversifies cropping systems but also increases yield and revenue, plausibly reduces input costs, restores soil fertility, and promotes ecological stewardship in smallholder low input-low output systems[12–14]. More importantly, if it enhances food security and nutrition security, it could make a significant contribution to the advancement of SDGs[15,16].

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Previous meta-analyses have established that legume pre-crops enhance subsequent crop yield by 20-32% with diminishing benefits under high nitrogen application[17–22]. However, information on how non-legume preceding crops affect subsequent crop yield is scattered across individual studies, with limited focus on their potential to close the yield gap. Moreover, there is a dearth of comprehensive global studies that simultaneously measure and compare the impact of non-legume and legume pre-crops on crop yields, particularly given that monoculture dominates in regions like Africa, South Asia[4,23,24], while rotations are prevalent in North America, Europe, and Australia[25–27]. Notably, despite extensive meta-analyses focusing on subsequent yield benefits, no synthesis has evaluated how rotation (the whole crop sequence i.e., pre-crop plus main crop) affect crop nutrients, calories - key health aspects of food security. Changing from continuous monocultures of high-yielding crops to rotational cropping via planting a preceding crop might lower overall multi-year total yields, and thus might decrease the dietary energy and nutritional value of the food supply, potentially threating nutrition security. Similarly, understanding the trade-offs related to the whole system revenue during the transition to more diverse sequences is crucial for farmers. Meanwhile, estimating profit in global meta-analyses is challenging due to the lack of input cost data, therefore, gross revenue comparisons could provide initial insights to assess financial trade-offs.

To date, no meta-analyses has comprehensively synthesized the trade-offs between total yields, dietary energy, nutrition and revenue at the system level. Such analyses are essential for designing crop sequences that synergistically enhance both food security (quantity) and nutrition security (quality), while maintaining farmer income. This multidimensional assessment represents a critical step toward implementing the UN Sustainable Development Goals' dual mandate of achieving zero hunger (SDG2) and ensuring sustainable consumption patterns (SDG12).

Here, we investigate whether transitioning from monoculture to crop rotations would be hampered by trade-offs between key outcomes related to food security and revenue. Through a global meta-analysis of 3663 paired field trial observations from 738 experiments, we systematically quantify how crop rotations - encompassing both legume and non-legume pre-crops (Fig. 1a) – affect agricultural sustainability across three critical dimensions: yield performance, nutritional output (dietary energy, protein, and micronutrients), and revenue. Crucially, we identify dominant cropping systems across continents and pinpoint regionally optimized sequences that simultaneously enhance yield, dietary energy, nutrition and revenue gains, providing actionable pathways to reconcile agricultural productivity with food security and economic viability.

Results

Yield gain of legume and non-legume pre-crops across continents

The effects of a large range of legume and non-legume pre-crops on subsequent crop yields were quantified using data from six continents (Fig. 1a). Overall, crop rotation increased yields of subsequent crop by 20% (95% confidence interval (CI): 16% – 24%, $P < 0.0001$) as compared to monoculture (Fig. 1b, Source Data). Legume pre-crops resulted in a yield gain of 23% (CI: 19%–28%, Fig. 1c) to the subsequent crop, which was significantly greater than that with non-legume pre-crops (16%, CI: 11%–21%, $P < 0.0001$, Fig. 1d, Source Data).

When averaged across legume (grain legumes e.g., cow pea, soybean etc.; green manure/fodder legume e.g., alfalfa, vetch etc.) and non-legume (cereal grains, cotton, tuber crops and grass fodder) pre-crops, the yield gain from crop rotation varied with continent (Source Data). The largest yield gain (27%, CI: 6%–53%, Fig. 1e) was observed in Oceania, where persistent break crop benefits promotes yields[28] followed by Asia and Europe, then Africa, South America and North America. The significant difference in yield gain between legume and non-legume pre-crops was found in Africa and North America, with the former witnessing the yield gain of legume pre-crops (29%, CI: 13%–47%) significantly higher than that of the latter (16%, CI: 10%–22%).

Yield gain varying with functional groups, crop species and their sequence

Pre-crops from different functional groups have distinct impacts on the yields of subsequent crops. With data from over 679 experiments, we analyzed more than 150 different crop pairs from different functional groups. We found that the functional group of pre-crops had significantly influences on the productivity of subsequent crops, but the amplitude of the effect varied according to the functional group considered (Fig. 2a). When pre-crops were grown as crop mixtures (species belonging to different functional groups), subsequent cereals had an 60% (CI:44%–79%) yield increase. Legume crops increased subsequent cereal crop yield by 20% (CI: 15%–25%), twice the effect size estimated when crops were grown in the reverse order. When rotated with other non-legume preceding groups (tubers, oil, grass fodder, fiber crops), cereal crop yield increased by 15% (CI: 4%–27%). This highlights the critical role of crop functional group when designing crop rotations to close yield gaps.

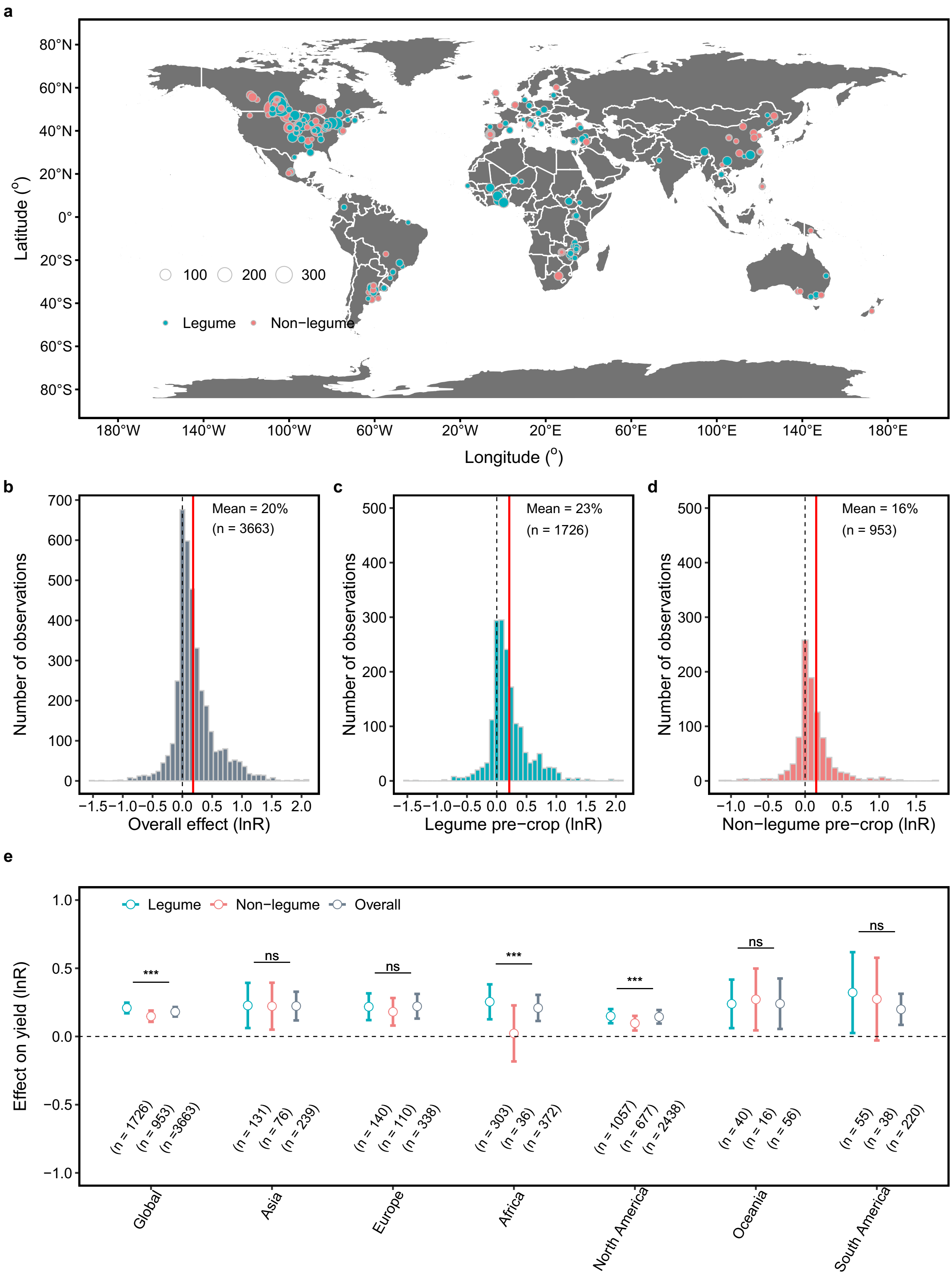
Yield gain of rotation to the subsequent crop differed in pre-crop species and crop sequence (Fig. 2b). The yield gain for wheat following faba bean was significantly higher than if following chickpea or pea. Fodder legume pre-crops increased subsequent cereal yield gain by 26% (CI: 20%–32%), with the strongest yield increase obtained by maize (83%, CI: 48%–128%). Notably, growing cotton before maize or maize before cotton results in high yield gain of both crops. The rotation effect was not always significantly positive. There were some crop combinations with statistically insignificant yield increase for the subsequent crop (Supplementary Figs. 3–6, Supplementary Tables 4–6, Source Data).

We examined how the yield gain of rotation varies over time and assessed its temporal yield variability, using 1159 paired yield observations from 230 long-term rotations experiments which spanned 9–50 years after initiation. We found that the effect of crop rotation on yield strengthened over years regardless of whether legumes or non-legumes were used as pre-crops compared to monoculture (Supplementary Fig. 1a). Mixtures, grass, fiber, legume fodder pre-crop types were associated with larger yield increases through time (Supplementary Fig. 1b). The year-to-year yield variability of the subsequent crop (lnCV) was 0.21 (CI: 0.06, 0.36, $P = 0.0059$), representing a higher yield stability in rotation than in monoculture (CV rotation < CV monoculture, see Methods, Supplementary Table 1). This result shows that crop rotation can help stabilize yields in response to climatic variability.

Based upon 2234 paired yield observations from 331 experiments, we found that the positive benefits of rotations tended to decline with higher nitrogen fertilization rates over time (Supplementary Fig. 2, Supplementary Table 2). Rotating maize or wheat with legumes reduced N fertilizer input for these staple crops by 41% – 46% compared with continuous maize or wheat monoculture while maintaining high cereal yields (Supplementary Table 3).

Rotation increases dietary energy, nutrients, and revenue

Crop rotations may have an opportunity cost, which is the difference between the production (yield, nutrition, or revenue) provided by a rotation and the production level provided by a monoculture of the rotation's highest-value crop. To provide insights on this opportunity cost, we sum yield, nutritional production, and revenue for the rotation sequence (pre-crop and subsequent crop) and compare the resulting values to those obtained with a monoculture of each crop species. Yield data for both crops in the rotation is available for 609 paired observations from 114 experiments. In average across all crop



combinations, rotation increased total yields, dietary nutrition and revenue of the whole system (i.e., the sum of pre-crop yields plus main-crop yields) when compared to continuous monocultures (Fig. 3a, Supplementary Table 7, Source Data). Specifically, total yields were increased by 23% (CI: 16%–31%) and dietary energy and protein quantities were increased by 24% (CI: 16%–32%) and 14% (CI: 8%–21%), respectively. Additionally, crop rotation increased micronutrients quantities in the order of iron (Fe), magnesium (Mg) and zinc (Zn) by 27% (CI: 15%–40%), 17% (CI: 10%–25%) and 17% (CI: 9%–25%), respectively. Revenue from crop rotation was increased by 20% (CI: 12%–29%) compared to the comparable continuous monocultures.

We found some strong cases of win-win-win scenarios for dietary energy, nutrition, and revenue (Fig. 3b–f, Supplementary Table 8, Source Data). Specifically, four crop rotations were highly beneficial by

Fig. 1 | Distribution of yield data across geographical regions and pre-crop effects. a Global distribution of yield data used in this study. The symbols on the map represent the experimental locations, the color represents legume and non-legume-based rotations, and the number of observations from each location is indicated by count. **b**–**d** Histograms of natural log yield ratios (lnR) showing legume and non-legume pre-crop effects on yield, respectively. The vertical red lines indicate the mean effect size, while the black broken line represents line of no effect at 95% confidence intervals. n represents the total number of observations. **e** The legume and non-legume pre-crop mean effect sizes across different regions. Open circles denote the overall mean effect sizes, with their associated 95% confidence intervals (CIs) indicated by vertical bars. Error bars not overlapping across 0 mean significant increase at $P < 0.05$ compared to monoculture. An ANOVA with two-sided and post-hoc pairwise comparisons was conducted with Tukey's HSD test for the significance test among different groups. ** and *** represent $P < 0.01$ and $P < 0.001$ between legume and non-legume pre-crops, respectively. ns represents no significance. Global and North America were highly significant ($P < 0.0001$). Africa was significant ($P = 0.0084$). Europe, Oceania, and Asia were not significant (Europe, $P = 0.192$; Oceania, $P = 0.7194$; Asia, $P = 0.9357$). The base map layer of country boundaries and coastlines was sourced from Natural Earth project (naturalearthdata.com). Source data and full statistical results are provided in the Source Data file.

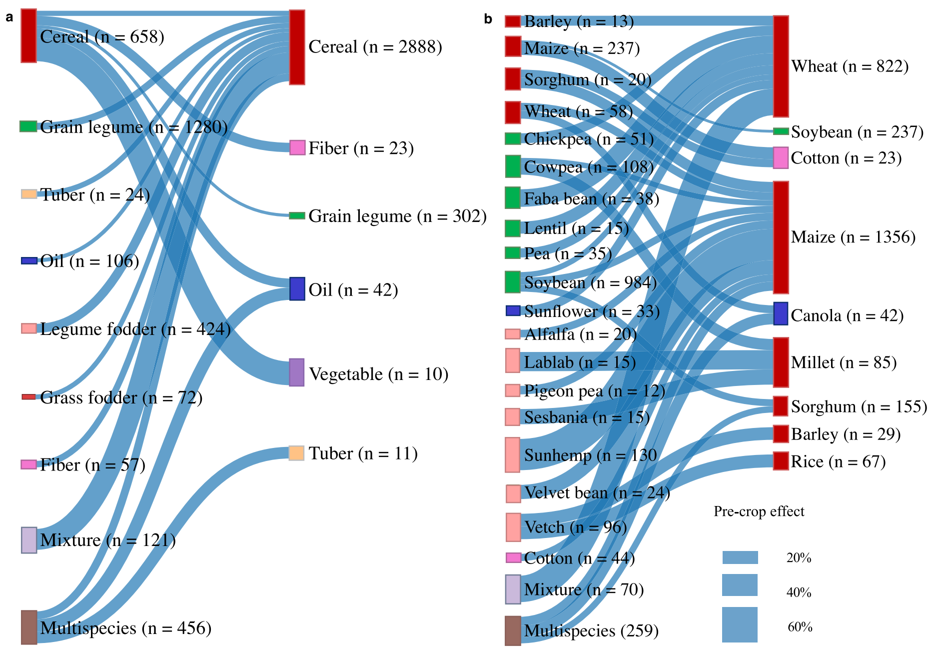


Fig. 2 | Associations between pre-crop groups or pre-crop species in rotations and their effect on subsequent crop yield. a Effects of different pre-crop functional groups (left) on yield of various subsequent crop functional groups (right) as compared to monoculture. **b** Effects of different preceding crop species on yield of various subsequent crop species. The flow width, represented by the scale on the right, indicates the magnitude of the pre-crop group/species on the subsequent crop group/species yield (% yield increase). Only crop sequences with significant mean effect on yield ($P < 0.05$) were represented. The number in parenthesis indicates the total number of observations and situations with $n < 10$ are not shown. Source data and full statistical results are provided in the Source Data file.

increasing dietary energy, nutrition, and revenue. Maize-soybean and sorghum-soybean were significantly better compared to a continuous soybean monoculture. In addition, maize-wheat outperformed continuous wheat monoculture while sorghum-maize provided better outcomes than continuous maize monoculture (Fig. 3g, Supplementary Figs. 7–8). In contrast, switching from monoculture maize to soybean-maize or monoculture sorghum to soybean-sorghum rotation incurred decreases by 27%, 53% and 50% for total dietary energy, micronutrients, and revenue, respectively (Fig. 3g, Supplementary Table 8). Similarly, transitioning from sorghum monoculture to maize-sorghum rotation resulted in 32%, 23% and 31% losses in yield, nutrition and revenue, respectively.

Based upon the above synthesized knowledge, we recommend specific crop sequences depending on the production context in different global major agricultural production regions, and highlight their potential in enhancing crop yields, nutrition and revenue (Fig. 4). In regions where crop rotation is been predominant, we highlight the yield losses that maybe associated with transitioning from rotation to continuous monoculture of specific crop species. For instance, in Europe, where continuous monoculture is less common, shifting from the predominant wheat-barley sequence to continuous wheat monoculture would lead to total yield, dietary nutrition, and revenue losses of 21%, 25% and 15%, respectively. Importantly, larger benefits greater than 80% for yield, nutrition and revenue can be realized by adopting appropriate rotations in monoculture-predominated regions especially West & Southern Africa and South America (Fig. 4). Thus, our results provide evidence that at global scale, some specific crop rotations can not only increase subsequent crop yield, but also improve total yields, dietary energy, nutrients, and revenue.

Discussion

Our comprehensive analysis of more than 3660 paired yield observations from 738 experiments showed that a wide range of crop rotations covering various crop functional groups/species can significantly increase crop yields, dietary nutrition and revenue simultaneously. The prevalence of win-win-win situations (i.e., achieving high yields, dietary energy and nutrition, and higher revenue) in our study highlights the prospective benefits of implementing a variety of crop rotation strategies[2]. These findings demonstrate that, in most cases, the adoption of crop rotation predominately avoids trade-offs between key outcomes related to food security and profitability. Nevertheless, a few types of rotations do not consistently provide such benefits, highlighting the need to provide tailored solutions on rotations that conform with different production contexts. These results have global

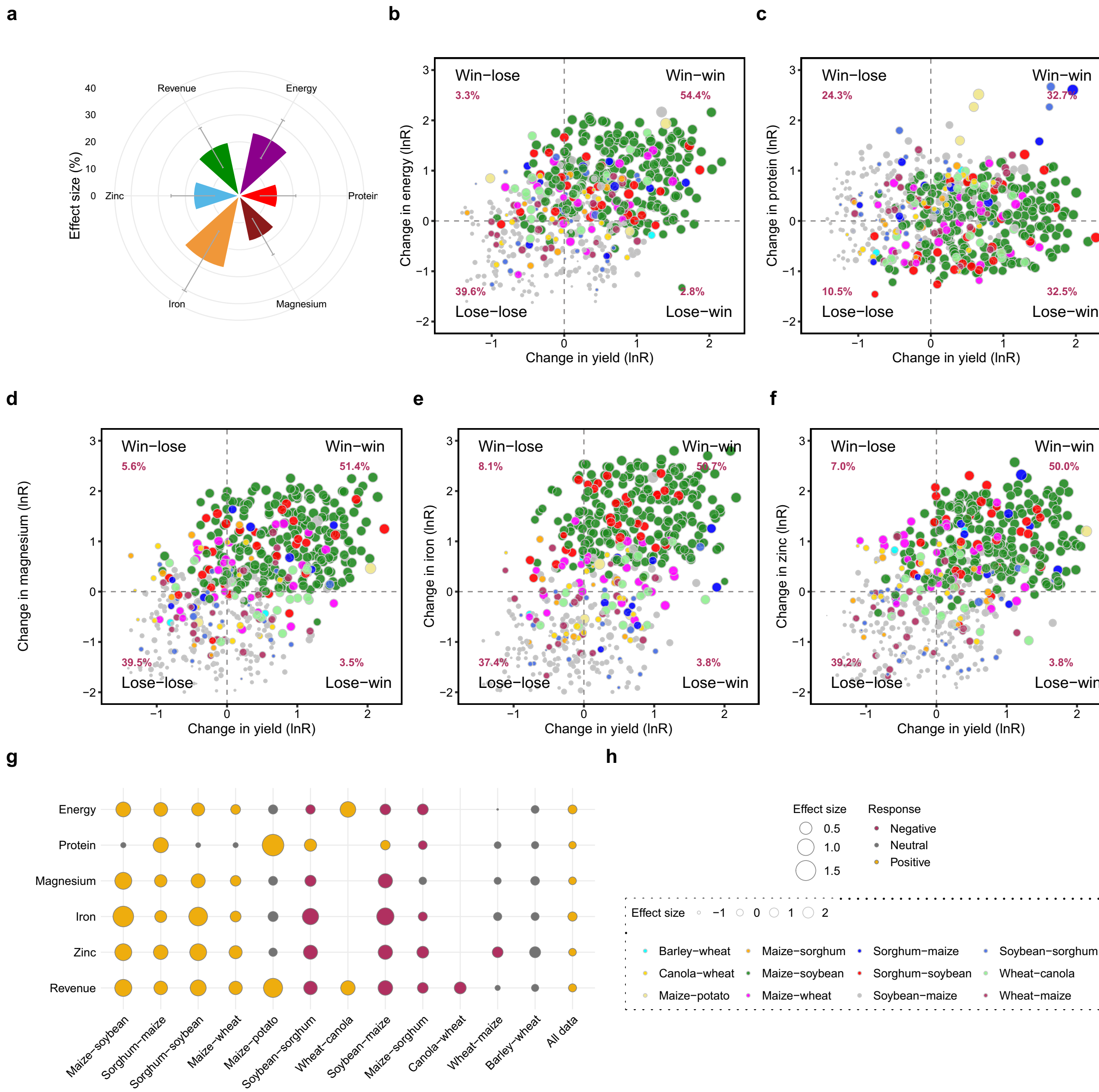


Fig. 3 | Crop rotation generally promotes high dietary energy, nutrients provision and higher revenue compared to monocultures. a Overall effects of the whole system compared to monoculture. The scale on the top left represents the effect size as a percentage. The gray error bars indicate the upper and lower confidence intervals of the mean at 95%. Effect sizes for energy, protein, magnesium, and zinc were derived from a sample size of $n = 609$; iron was derived from $n = 591$. **b**–**f** Assessment of trade-offs between yield and dietary energy, protein, magnesium, iron and zinc plus the associated change in revenue based on averaging yields of all pre-crops and subsequent crops, for all rotational crop sequences, and comparing these average annual yields to monocultures of subsequent crops, respectively. In each cropping sequence, the last crop (e.g., maize in soybean-maize) represent the specific monoculture that was compared to that specific sequence. The points depict combinations of effect sizes for yield, dietary nutrients, and revenue based on crop sequences in the bottom legend. The symbol size was based on the revenue effect sizes (bottom legend). The proportion of effect size combinations between yield and dietary nutrients in each quadrate is indicated in red. **g** Summary of crop sequences' effects on yield, dietary nutrients and revenue from mixed effects models (lme) are presented (top legend). "Negative," "Neutral" and "Positive" signify a significant increase, non-significant change and significant decrease for the variable respectively at ($P < 0.05$). **h** The top legend represents the effects in panel **g**. Crop sequences corresponding to symbols in **b**–**f** are show (bottom legend). An ANOVA with two-sided and post-hoc pairwise comparisons was conducted with Tukey's HSD test for the significance test among different crop sequences. Source data and full statistical results are provided in the Source Data file.

implications to help meet food and nutrition security goals by 2030 and beyond.

Different from previous meta-analysis, we analyzed and compared the rotation effect of both legume and non-legume pre-crops on yields of subsequent crops across different continents. Interestingly, our study revealed surprisingly a large yield gain (i.e., 16%) induced by non-legume pre-crops (e.g. sorghum, barley, wheat, etc.), with this effect strengthening over time, despite the inability of such pre-crops to fix nitrogen[29]. This may occur because non-legume pre-crops can promote decomposition or soil aggregation[30,31], or are deep-rooted and may increase soil moisture via hydraulic effect[32], or may create biopores that improve soil structure[33]. Non-legume pre-crops can limit

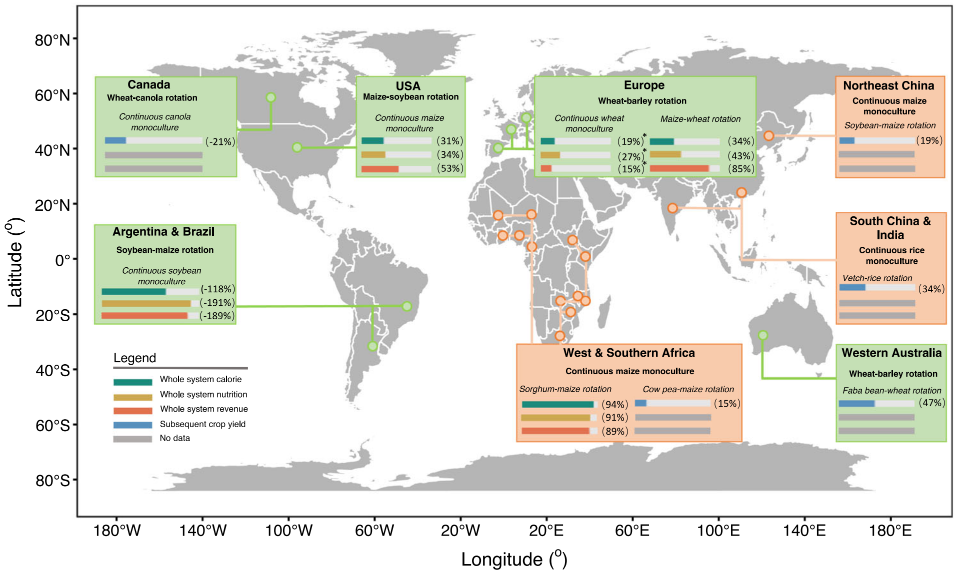


Fig. 4 | Yield, dietary nutrition and revenue benefits of rotation vs. monoculture systems in major agricultural production regions worldwide. Light green and peach circles represent major agricultural production regions where the current predominant cropping system (specified in bold) is rotation or continuous monoculture, respectively. Values in percentages indicate the benefits/losses comparing an alternative system (indicated in italics, representing either the recommended synergized crop rotation or a monoculture (frequently used in the region considered) with the current predominant cropping system in a specific region (indicated in bold). Trade-offs were calculated for total yield (green bars), dietary nutrition (yellow bars) and revenue (orange bars) of the whole system (i.e., preceding crop plus main crop) between the above-mentioned systems where data were available. Royal blue bars indicate the yield gain of the subsequent crop through alternative rotations, or otherwise how much yield proportion would be lost by not transitioning from monoculture. Bar lengths are capped at a 100% reference value for all regions except Southern America, which is capped at 200%. * indicates non-significant outcomes between the dominant system and continuous monoculture. In each cropping sequence, the last crop (e.g., maize in soybean-maize) represent the specific monoculture that was compared to that specific sequence.

disease development or if non-hosts, they could break pest and disease cycles[34,35] or can increase soil phosphorus availability by associating with arbuscular mycorrhizae[36–38].

As expected, legumes as pre-crops on average showed higher yield gains (i.e., 23%, on average) than non-legumes (i.e., 16%), which agrees with previous studies[17,22]. Grain legume crops, despite their ability to fix nitrogen, typically result in a negative nitrogen balance as they export more nitrogen than they fix. The positive benefits could be primarily because they help prevent nitrogen depletion in the soil during their decomposition[39]. The largest yield benefits were in Africa, underscoring the importance of leveraging legumes in this region[40–42], in relation with low nitrogen fertilizer rates applied by most African farmers[14]. Nonetheless, legume adoption coupled with increased fertilizer in non-legume-based sequences for African farmers may strategic in closing the yield gap. However differences between legume and non-legume rotations were not always significant, especially in Asia and Europe, where fertile soils or high residual fertilizer enhance yields of subsequent crops, irrespectively of the presence of legume crops in rotations[43,44]. Balancing nutrient use to sustain high and stable yields, reducing fertilizer dependance, mitigating environmental risks, and cutting input costs remain as challenging[45].

The yield benefits of rotation increased through time, which was consistent with previous meta-analyses[19,22]. However, our study showed that while the rotation benefit increased over time, higher inorganic nitrogen application, particularly in legumes, may counteract these benefits by suppressing biological nitrogen fixation[46,47]. This suggests the possibility of increasing crop yields while lowering the nitrogen rates for subsequent crops, ultimately reducing environmental pollution. The greater positive effects of the mixture pre-crops (intercrops of grasses and fodder legumes) are probably due to complementarity of species, suggesting an opportunity for improving yield and soil health[48,49]. Our study expands the understanding of the positive benefits not only associated with legume pre-crops, but other non-legume pre-crops on subsequent crops yields and their temporal stability. This suggests that in the face of increasing climate change risks[50,51], crop rotations can provide higher total yields with optimized nitrogen fertilizer compared to monoculture[18,22,52], offering a dual pathway to enhance productivity while mitigating environmental pollution.

Our analysis provides a better understanding of the trade-offs between total yields, dietary energy, nutrients and the associated changes in revenue when transitioning from monoculture to crop rotations. This is an important contribution to the scientific literature because previous meta-analyses mainly focused on subsequent crop yield benefits. In our study, crop rotation generally increased total yields, dietary energy, nutrients and revenue. This suggests that crop rotation can be a key strategy to increase food availability while diversifying human diets by providing high-quality proteins and micronutrients, thus achieving food and nutrition security, while at the same time increasing the farmers' income. Maize, an important staple crop in many African countries, has seen increased land allocation over the last few decades compared to other crops[4]. While maize yields are generally low due to low fertilizer application, use of open-pollinated varieties, poor infrastructure[53] and continuous monoculture among a myriad of reasons, legume pre-crops such as cowpea, peanut, and soybean can be beneficial to subsequent maize. Meanwhile, promoting non-legume rotations in the same region, especially sorghum-maize, instead of continuous maize monoculture, or were legumes fail agronomically holds great potential to increase transgressive overyielding[49], since both crops are highly dominant and adapted to adverse conditions[54,55], offering greater yields, dietary nutrients and higher revenue compared to maize monoculture.

Based on our findings, we were able to identify strategic cropping sequences elsewhere that could simultaneously increase both yields, dietary nutrition and revenue simultaneously. Even though soybean-maize rotation is dominant, continuous soybean monocultures are still practiced in South America, especially in some parts of Brazil and Argentina, given the high market demand, established processing infrastructure, and export dominance[23,24]. Our findings show that cereal-legume rotations in South America offer high yield benefits, more so with maize-soybean and sorghum-soybean rotations presenting the most significant win-win-win outcomes. These findings demonstrate the potential to increase chances of overyielding by including maize or sorghum in rotation systems, as they often bring high yield, dietary energy, nutrients and more revenue. Thus, adopting these rotations could enhance sustainability and productivity in South America and other regions where soybean monoculture is dominant. While wheat-based rotations dominate the wheat belt in Western Australia[27], our findings suggest that monoculture wheat results in more that 20% loss of the yield advantage from legume-wheat-based rotations. Similarly, rice and maize yields could greatly be improved if rotated in the South Asia and Northeast China, respectively.

As crop rotations have been widely recognized for their benefits over monoculture, they have been broadly adopted in Europe due to favorable public regulations[26]. Ongoing research comparing crop rotations with monocultures are conducted in Europe to better understand the mechanisms explaining the positive effects of rotations. Despite their disadvantages, monocultures of maize in the Southern Europe, rice, rye, oats, cotton and barley in the Northern Europe persist[56]. We found in this study that dominant rotations like wheat-barley may yield the same output as monoculture wheat, yet alternative rotations like wheat-maize results in transgressive overyielding. Similarly, while maize-soybean rotations are dominant in North America, evidence suggests a decline in rotation practices[57], likely driven by the market incentive favoring maize monoculture[58]. By rotating maize with soybean, farmers in the USA lose at least 19%–53% of the total yield, dietary nutrition and revenue accrued from continuous maize monoculture. Although maize-soybean rotations have lower yield and revenue than continuous maize monoculture, they are often preferred by North American farmers because of the lower costs of maize-soybean rotations, which lead to higher overall profits. More than 50% of national sorghum in the USA is produced in the Midwest or Central Plains[59]. Our findings suggest that sorghum-maize rotations offer greater win-win-win outcomes, indicating that non-legume-based rotations may be a more sustainable option in these regions.

Despite legume-based rotations offering yield advantages to the subsequent crop, careful planning is essential, particularly when transitioning from high-yielding monoculture maize to soybean-maize rotations, as there is the possibility of "transgressive underyielding," where a rotation performs less than a lower-yielding monoculture. Our study found significant imbalances between dietary energy, nutrients and revenue with soybean-maize rotation compared to maize monoculture. Transitioning from sorghum monoculture to soybean-sorghum or maize sorghum was also costly in terms of total yields, dietary nutrition and revenue. This implies that in regions with significant dietary protein or other nutrient deficiencies, other rotations tailored to supply the essential missing nutrients should be adopted. However, the results reflect controlled experimental conditions, which may differ from real-farming scenarios where management practices, input costs, and climate variability interact more dynamically. While our analysis of revenue impacts provides valuable insights into how crop rotations affect farm budgets, it is important to note that this dataset does not include detailed information on farm operations and production costs. These cost data would be necessary for calculating actual profitability, which is critical to fully understand the economic implications of rotation systems. Nevertheless, the revenue metrics serve as a meaningful proxy that allows for preliminary assessment of rotation effects on financial outcome. More importantly, to alleviate both food insecurity and "hidden hunger" problems, advancing SDG 1–2, we strongly advocate for the adoption of crop rotations not only guided by high subsequent crop yield goals but also by the potential to enhance high total energy and nutritional value while improving farmer's revenue[60,61].

In conclusion, our study demonstrates that various types of crop rotation positively impact production, income, and nutrition, highlighting the role of crop diversification in enhancing food security. Furthermore, we were able to identify specific beneficial crop rotations in different global major agricultural producing regions offering actionable guidance for sustainable food and nutrition and income security. Notably, there is potential to close yield gaps with non-legume rotations in high-input systems, while legume rotations are more beneficial in resource-constrained farming. However, widespread adoption remains a challenge, particularly in the Global South, where economic constraints and agronomic uncertainties limit implementation. To overcome these barriers, integrating agricultural crop diversification into national policies and fostering collaboration among stakeholders is essential[62]. This approach can reduce reliance on synthetic inputs, lower environmental impacts, and combat "hidden hunger". Ultimately, regionally adapted and field-tested crop rotations under real-farming situations can play a pivotal role in securing food and nutrition, increasing farm profitability, and advancing global sustainability goals[60,63].

Methods

Data collection

An extensive literature search was conducted in the Web of Science core collection (http://www.webofknowledge.com), to collect relevant information published from 1980-2024. We used a combination of keywords in the topic field: TS = ("pre-crop*" OR "preceding crop*" OR "precursor crop*" OR "previous crop*" OR "crop* rotation*" OR "sequential crop*" OR "sequence*" OR "crop sequence*" OR "successive crop*" OR "ley farming" OR "green manure*" OR "cover crop*"). An additional search was conducted in Google Scholar (the first 5000 records) (http://scholar.google.com) using key words "crop rotation", "pre-crop", "preceding crop" and "cover crop". The identified publications were screened for relevance. Detailed searching and screening procedures based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-analyses) are shown (Supplementary Fig. 9).

Study selection

To be included in our dataset, the experiment had to meet the following criteria: 1) the rotation experiment was conducted under field conditions; 2) a control, that is a cropping system where a single crop species was grown in continuous monoculture, and at least one rotation treatment defined as a crop sequence where the pre-crop species was different from the subsequent crop species was included; 3) the preceding and subsequent crop species were explicitly identified; 4) the yield of the subsequent crop and its corresponding yield when grown in continuous monoculture were recorded; 5) the experiment included replications. Multiple records were extracted from multiple experiments in each study and multiple experiments in each treatment. "Experiment" was defined as a unique combination of site and year. We collected relevant data from each study, including location (i.e., region, longitude, and latitude), mean annual precipitation, mean annual temperature, soil texture, initial levels of soil organic matter, soil organic carbon, total nitrogen, crop species, years of rotation, number of replications (Supplementary Table 9). Data from tables were extracted directly for each observation consisting of the mean of the control and treatment at the same site and year. Data presented in the form of figures were extracted using WebPlot Digitizer Version 4.3 (https://automeris.io/WebPlotDigitizer/).

We aimed to assess the effect of both legume and non-legume pre-crops on both legume and non-legume crop yield. To achieve this, we identified features of control and treatment including preceding crop species, crop types, pre-crop purposes, subsequent crop species, subsequent crop type, and residue management in both instances. We classified the pre-crops first into two broad groups (i.e., legume and non-legume) to represent rotation systems with or without a legume. Pre-crops were then further classified based on their functional groups as defined by FAO[64], to capture the functional diversity effects among different groups on yield. Legumes were classified as either grain legumes or fodder legumes (green manure legumes). We included groundnuts and soybean as grain legumes due to their N-fixation capabilities, even though they are identified by FAO as oil crops. Other groups included grass fodder, cereal, tuber, fiber, vegetable, oil crops and the same approach was applied for subsequent crops. We did not include soybean and groundnuts in the oil group to avoid duplication. Where the subsequent crop was followed by fallow, we investigated the effect of fallow as a separate group. When a grass was grown together with a fodder legume before the subsequent crop, we categorized them as mixture. In cases were several crops preceded the main crop, we categorized them as multispecies. Only 20% of all the studies included some form of cover crops, grown individually, or within a sequence of multiple crops before the main crop. Other management practices such as tillage, nitrogen fertilizer rate, and irrigation were recorded either as categorical or continuous when applicable. We treated tillage as either conventional, conservation, or no-tillage, where conservation included strip-till, ridge-till and conventional included moldboard plow, chisel plow, subsoiling, or deep tillage. Irrigation was recorded as either rainfed or irrigated when data was available, and the cells were left blank in unclear circumstances. In total, we finally compiled a data set with 162 publications in English across five continents with 3663 paired observations on yield (Supplementary Note 1).

Data analysis

The data extracted from the individual studies were used to compute the natural logarithm of the response ratio as the effect size to measure the effect of crop rotation on subsequent crop yield Hedges et al.[65].

$$\ln R = \ln(X_t/X_c) = \ln(X_t) - \ln(X_c) \tag{1}$$

where X_t and X_c are the subsequent crop yield values in a rotation treatment (i.e., pre-crop different from the subsequent crop) and a monoculture control (i.e., pre-crop identical to the subsequent crop) respectively. The mean effect sizes were estimated using a mixed-effect model including the publication and the experiment within publications as random effects to account for differences among studies (publications) and the experiments (site x years) within studies[66]. This modeling approach was essential because it accounts for the non-independence of multiple effect sizes originating from the same study or experimental site. Additionally, it accommodates the inherent heterogeneity in our global dataset arising from variations in covariates related to environmental conditions, management practices, and experimental designs across studies[67–70]. The statistical significances of these covariates were tested ($P < 0.05$) and their importance was evaluated using AIC, confirming their necessity for robust effect size estimation. Mean effect sizes were estimated using the whole dataset and for several subgroups corresponding to different types of pre-crops and subsequent crops. Due to the limited number of studies reporting standard errors or confidence intervals in more than half of our studies, we did not weigh the individual studies for estimating the mean effect sizes[71]. Excluding those papers would significantly limit the number of records in the dataset, making the results of subsequent analyses less accurate than the one we performed. Unweighted analyses have been commonly used in agricultural science, including agricultural diversification studies focusing on crop rotation[72], and can provide a valid and unbiased evaluation[73]. The benefit of an unweighted analysis is that a larger set of source papers is suitable for analysis, thus increasing the number of studies that is available for meta-analysis[74]. Meta-regressions were also fitted by adding covariates (N fertilizer rates or length of rotation, defined as fixed effects) in mixed-effect models. Any record consisting of missing data were excluded from the analysis requiring that variable. When 95% confidence intervals were overlapping with zero, the corresponding effects were considered as nonsignificant ($P < 0.05$). The response ratio was back-transformed to generate a percentage of yield change due to rotation (E+), for an easier interpretation of the results:

$$E^{+} = (\exp^{\ln R} - 1) \times 100 \tag{2}$$

All analyses were conducted in the R Statistical Software Version 4.2.2[75]. We fitted linear mixed-effect models using the *lme* function of the R package *nlme* to estimate the average values of lnR for yield (Supplementary Table 10). The R function AIC (Calculating Akaike's information criterion) and ANOVA (Analysis of Variance) were used to identify the best random effect structure and model selection. We fitted linear mixed regression models with *lme* for estimating the pre-crop effect on subsequent crop yield as a function of several covariates related to rotation years, crop sequence types, and nitrogen fertilizer rate. The statistical significances of these covariates were tested ($P < 0.05$) and their importance were evaluated using AIC. We found that the most important covariates were nitrogen input and cropping sequence as these covariates were included in the top ten models, i.e., the ten models with the lowest AIC (Supplementary Table 11). Funnel plots relating effect sizes to sample sizes were used to determine whether there was evidence of publication bias[76]. The study size was defined as the total number of replicates over all records per study (Supplementary Fig. 10). Funnel plots did not reveal any publication bias. To further confirm the validity of results from the funnel plots, we ran the global model (Model 1, Supplementary Table 10) to assess whether the studies based on fallow affected the results. We also re-ran the global model based on another dataset after removing all studies with some form of cover cropping. Finally, we conducted a sensitivity analysis using a "leave-one-out" method[77]. The results showed consistent estimates, standard errors and *P*-values, suggesting that no single study was disproportionately influencing the overall meta-analysis results.

Crop rotation assessment for human dietary nutrition and revenue

Because the data available for preceding crops in some of the experiments was limited, we selected trials where data on subsequent crop and pre-crop yield were available in order to assess the trade-offs in dietary energy, nutrients and the associated revenue generated by rotation as opposed to monoculture. Studies reporting yield data for the monoculture, previous crop, and subsequent crop were chosen from the database. We excluded crop sequences including mixtures, fallow, as well as those including cotton as either a pre-crop or subsequent crop because we focused on crops grown for human dietary nutrition. The final data included 609 paired yield observations across different cropping sequences. Next, using the yield from monoculture and rotation, the total dietary nutrient yield was determined by multiplying the yield per 100 g of each crop by the standard values of dietary energy (Kcal), proteins, iron, zinc, and magnesium obtained from (FoodData Central (usda.gov). The natural logarithm of the dietary nutrient response ratio for each nutrient was calculated as:

$$\ln R_{nutrients} = \left(\ln \frac{(Precropyield*Pnc) + (Maincropyieldinrotation*Mnc)}{2(Monocultureyield*Nc)} \right) \tag{3}$$

where *Pnc*, *Mnc* and *Nc* represent pre-crop, subsequent crop and monoculture nutrient content in grams per dry matter, respectively.

To estimate the revenue from rotation compared to monoculture, we first multiplied the total yield for each system by an average annual producer price (USD/ton) of the specific crop in a specific country between 2008 – 2018. Producer prices for various crops from different countries are available from data managed by FAOSTAT. The natural logarithm of the revenue response ratio was then calculated as:

$$\mathrm{lnR}_{revenue} = \left(\ln\frac{(Precropyield*Prev) + (Maincropyieldinrotation*Mrev)}{2(Monocultureyield*Nrev)}\right) \tag{4}$$

where P*rev*, M*rev* and N*rev* represent pre-crop, subsequent crop and monoculture gross revenue, respectively. The same procedure as for yield (see above, Supplementary Table 10) was then implemented to estimate the mean effect sizes. When 95% confidence intervals of the estimated mean effect sizes were overlapping with zero, the corresponding effects were considered as nonsignificant ($P < 0.05$). In order to facilitate result interpretation, the data were back-transformed to produce a percentage of dietary nutrient yield change as a result of rotation.

Proportion of N-savings in crop rotations

To calculate the amount of fertilizer that can be saved by crop rotation as opposed to monoculture, we classified various fertilizer application scenarios in the database. The field trials' approaches of applying fertilizer varied greatly. Since potassium and phosphorus were often given consistently to all treatments at basal dressing, we were unable to identify appropriate sample sizes for these analyses. A total of 29 articles from the database indicated that the nitrogen fertilizer was applied to the subsequent crop only (preceding crop unfertilized); these studies corresponded to 1332 paired yield observations. In only 7 studies with 73 paired yield observations, nitrogen fertilizer was applied to the previous crop alone, without N fertilizer application to the subsequent crop. Fertilizer rates for the subsequent crop and the preceding crop were not available in 55 studies totaling 934 paired yield observations. We finally selected 20 unique studies with 359 paired yield observations where nitrogen fertilizer was applied to both the monoculture and rotation crops. The amount of nitrogen application saved was calculated as follows:

$$\mathrm{lnR}_{nitrogen} = \left(\ln\frac{Nprecrop(kg/ha) + Nmaincrop(kg/ha)}{(2*Nmonoculture(kg/ha)}\right) \tag{5}$$

where $\mathrm{lnR}_{\mathrm{nitrogen}}$ represents the ratio of total nitrogen applied in the rotation system, i.e., sum of $N_{precrop}$ (total nitrogen in preceding crop) and $N_{subcrop}$ (total nitrogen in subsequent crop) to total nitrogen required in continuous monoculture ($N_{monoculture}$).

Crop rotation effects on yield stability

To assess temporal stability of yield, we used only papers reporting yearly yields for more than 9 years since the beginning of the experiment to assess yield stability (between years) in rotation as compared to monoculture. Data meeting this criterion included 1159 paired observations of monoculture and rotation yields, with a maximum experiment length of 50 years, including three major cereals (maize, wheat, and rice), two minor cereals (barley and sorghum), and one major legume (soybean). Temporal (year-to-year) variability (CV, coefficient of variation) of yields in monoculture and rotation per study was defined as σ/μ, where σ is the temporal standard deviation of the yield and μ is the temporal mean yield over the number of years since the rotation started. We then used the natural logarithm of the CV (lnCV) from both monoculture and rotation to make the distribution symmetrical, allowing for performing a meta-analysis with a random effect, and included a bias correction term to make the estimator unbiased[70]. This approach allows for appropriately weighting long-term studies by using growing-season years as sample sizes, and standardizing stability comparisons across diverse systems through the coefficient of variation:

$$\mathrm{lnCV} = \ln\left(\frac{\mathrm{Sc}}{\mathrm{St}}\right) + \frac{1}{2(nc-1)} - \frac{1}{2(nt-1)} \tag{6}$$

where lnCV is the natural logarithm of the ratio between monoculture temporal stability (Sc) and rotation temporal stability (St), and nc, nt are sample sizes of monoculture and rotation respectively. The variance component was also calculated based on Nakagawa et al.[70]. We assumed that the rotation system was more stable over years of experimental period when the lnCV was less than zero, implying that interannual differences are small.

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

Datasets used to generate the figures are provided in the Source Data file. The underlying data for Fig. 2a, b are also available in Supplementary Tables 4 and 6, respectively. References to publicly available original data are listed in Supplementary Note 1. All other raw data are part of a students' ongoing PhD project and will be available from the corresponding author upon request. Source data are provided with this paper.

Code availability

All analyses were done in R (ver. 4.2.2) using the "nlme" package (ver. 3.1.162) for the meta-analysis. The R code is available from the corresponding author upon request.

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Author contributions
S.M., J.J. and W-F.C. conceptualized and designed the study and wrote the original draft. S.M., J.J. and W-F.C. collected the data. S.M., X.H., Z.L., T.C.W., D.M., J.J. and W-F.C. developed the methodology and performed the analyses and the visualization. W-F.C., J.J. and F.Z. secured the funding and supervised the project. and W-F.C., J.J., X.H., Z.S., T.C.W., D.M., D.T. and F.Z. reviewed and edited the paper.

Competing interests
The authors declare no competing interests.

Additional information
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