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Structural Capacity, Food Security-Related Publications, and Crop Production: A Multilevel Global Analysis Across Income Settings

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Abstract

Agricultural performance is often interpreted through agronomic inputs and technological progress; however, the translation of knowledge into production depends on the structural environments in which food systems operate. This study examined the association between food-security-related publication activity and crop production across global income settings from 2000 to 2025, while testing whether governance, health-system, and financial indicators modify that association. A longitudinal ecological panel was constructed, integrating 61,158 Scopus-indexed peer-reviewed articles on food security and related dimensions of healthy food access and availability with 23 crop production indicators grouped into staple, horticultural, and commodity domains. Income-stratified regression models were followed by hierarchical mixed-effects models and moderator screening. In exploratory stratified models, 67 of 92 income-specific associations reached nominal significance; however, only 5 of those 67 associations (7.5%) remained statistically significant after multilevel modelling and false discovery rate correction. Robust associations were concentrated in selected staple and horticultural outcomes, whereas most commodity indicators lost significance after hierarchical adjustment. Structural moderators related to territorial control, corruption, healthy life expectancy, health researcher density, healthcare access and quality, and official development assistance shifted the conditional slopes linking publication activity to crop output. These findings do not support a uniform linear relationship between publication growth and production volume. Instead, they suggest that the alignment between research ecosystems and agricultural output is structurally conditioned and likely mediated by institutional capacity, health-system resilience, and implementation environments. The ecological design, the use of publication counts as an indirect proxy, and the reliance on production volume rather than yield or efficiency should be considered when interpreting these results.

Keywords: food industry; food supply; crop production; research; socioeconomic factors

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1. Introduction

Agricultural production is often approached as a function of agronomic inputs (land availability, technological adoption, climatic conditions, and market integration) [1]. Yet, across income settings, production trajectories rarely reflect resource endowment alone [1]. Countries with comparable agroecological potential frequently exhibit markedly divergent yield patterns, stability profiles, and sectoral specialization [2]. Such divergence suggests that crop performance is embedded within broader structural environments that condition how agricultural systems absorb innovation, allocate resources, and respond to external pressures [2].

Structural capacity, understood as the composite of institutional effectiveness, governance stability, administrative coherence, and infrastructural robustness, shapes the operational context within which agricultural production unfolds [2]. It influences investment continuity, policy implementation fidelity, land tenure security, and the capacity to coordinate complex supply chains [3]. Where structural capacity is constrained, productivity gains may be fragile, localized, or unevenly distributed [2,3]. Conversely, where institutions function predictably and governance mechanisms are stable, agricultural systems may convert similar inputs into sustained production performance [2–4].

Within this structural landscape, scientific activity is best approached here not as a direct measure of agricultural innovation itself, but as an indirect macro-level signal of knowledge-production capacity in a specific thematic domain [5–8]. In the present study, the exposure was operationalized as food-security-related publication activity, measured through annual country-level counts of peer-reviewed Scopus-indexed articles explicitly addressing food security and related dimensions of healthy food access and healthy food availability [5,7]. This operationalization captures one segment of national research ecosystems relevant to food systems, but it does not exhaust the broader universe of agricultural research and development (R&D), extension activity, technological adoption, or innovation performance [6–8].

Assuming that greater publication output should translate directly into higher crop production presumes relatively frictionless knowledge diffusion, institutional uptake, and implementation capacity [6,7,9]. Empirically, however, the pathway from research production to agricultural performance is likely mediated by absorptive capacity, extension systems, regulatory environments, infrastructure, and socio-economic stability [6–9]. In some contexts, increasing publication activity may accompany structural transformation, crop diversification, sustainable intensification, or shifts toward higher-value sectors rather than simple volumetric expansion [7,10,11]. In others, weak institutional arrangements may attenuate, delay, or distort the observable relationship between knowledge generation and crop output [6,7,9].

These considerations suggest that crop production performance should be examined not merely as a function of scientific volume, but as the outcome of an interaction between knowledge generation and structural capacity. A systems-level perspective is therefore warranted (one that accounts for hierarchical income stratification, temporal dynamics, and contextual moderators capable of conditioning translational effects) [12].

Against this background, the present study examined whether food-security-related publication activity is associated with crop production across global income settings (between 2000 and 2025) and whether that association is conditioned by structural capacity. Specifically, three hypotheses were addressed. First, the association between publication activity and crop production would be heterogeneous across income settings and crop domains rather than uniformly positive. Second, structural indicators related to governance, health-system capacity, and financial assistance would significantly moderate that association. Third, after multilevel adjustment and false discovery rate (FDR) control, only a

limited subset of the nominally significant stratified associations would remain statistically robust. The originality of the study lies not in estimating direct agronomic productivity effects, but in evaluating how knowledge-production ecosystems align with crop-output trajectories within structurally heterogeneous food systems.

2. Materials and Methods

2.1. Study Design and Conceptual Framework

This study was conceived as a global longitudinal ecological analysis aimed at characterizing how structural environments condition the relationship between food-security-related publication activity and crop production performance within contemporary food systems. Rather than assessing discrete technological interventions or attributing yield changes to specific innovations, the design focuses on system-level co-evolution across countries and income settings over time [13].

To operationalize this framework, annual bibliometric records of food- and agriculture-related scientific production were harmonized with country-level indicators of crop production across major agricultural domains. Data were structured at the country-year level and subsequently stratified by World Bank income categories (Low-Income Countries [LIC]; Low-Middle-Income Countries [LMIC]; Upper-Middle-Income Countries [UMIC]; and High-Income Countries [HIC]) [14] to account for structural heterogeneity in economic capacity, institutional robustness, and agricultural system organization.

Publication activity was conceptualized as a measurable dimension of national knowledge-generation ecosystems embedded within broader governance, health, and administrative infrastructures. Crop production indicators, expressed in metric tons across staple, horticultural, and commodity crops, were treated as aggregate performance measures of food system output [15]. Examining these components jointly enables the assessment of whether and how the density of scientific activity aligns with production trajectories under differing structural conditions.

The analytical window spanned 2000 to 2025, a period marked by substantial global transformation in agricultural markets, technological adoption, and research investment patterns. Stratification by income group (LIC, LMIC, UMIC, and HIC) was incorporated to reflect systematic differences in institutional capacity, sectoral diversification, and absorptive potential (factors likely to shape the translational interface between knowledge generation and production performance) [14].

Consistent with the ecological and longitudinal nature of the analysis, the unit of inference was the country-year. The study does not attempt to isolate causal effects at the level of individual technologies or policies. Instead, it evaluates aggregate structural patterns, acknowledging that observed associations reflect complex system dynamics rather than linear innovation pathways [15].

2.2. Data Sources and Search Strategy

Food security-related publication activity was operationalized using peer-reviewed journal articles indexed in Scopus. Scopus was selected because it provides broad international coverage across agriculture, nutrition, food systems, and public health, together with standardized affiliation metadata that facilitates consistent country-level aggregation. Although the search strategy was considered sufficiently comprehensive for the purposes of this study, reliance on a single bibliographic database may have omitted relevant publications indexed in other pertinent sources, including Web of Science and regional databases; accordingly, the bibliometric exposure should be interpreted as a robust but bounded proxy of global food-security-related research activity rather than as an exhaustive census of all relevant literature.

The search was conducted on 5 November 2025. Search terms were selected a priori on conceptual grounds to identify publications explicitly focused on food security and closely related constructs of healthy food access and food availability. A high-specificity TITLE-ABS strategy was favored over a broader agri-food vocabulary in order to capture a thematically coherent subset of the literature rather than the entirety of agricultural science. The final search expression was:

TITLE-ABS ("Food Security") OR TITLE-ABS ("Access to Healthy Food*") OR TITLE-ABS ("Healthy Foods Availabilities") OR TITLE-ABS ("Healthy Foods Availability") OR TITLE-ABS ("Access to Health Food") OR TITLE-ABS ("Healthy Food Availability") OR TITLE-ABS ("Healthy Food Availabilities").

The initial retrieval yielded 80,309 records. To maximize comparability across countries and years, only peer-reviewed journal articles were retained. Conference papers, books, book chapters, errata, conference reviews, retracted publications, articles in press, and other non-article sources were excluded because they differ substantially in editorial filtering, indexing consistency, and country attribution, which could introduce additional heterogeneity into the bibliometric exposure. After sequential filtering, 61,158 articles remained in the analytic corpus.

For each record, publication year and corresponding-author institutional affiliation were extracted. Country assignment based on the corresponding author's institutional address was used as a pragmatic proxy of the national research environment from which the publication was coordinated. This approach does not fully capture multinational collaboration structures or distributed research networks, and this limitation is acknowledged in the Discussion. Annual publication counts were then aggregated at the country-year level and subsequently mapped to World Bank income-group classifications [14].

These aggregated measures were not interpreted as direct proxies of technological adoption or policy implementation. Rather, they were treated as macro-level indicators of knowledge-generation density within food-related scientific domains, enabling examination of how research ecosystems co-evolve with crop-production trajectories across structurally heterogeneous contexts.

2.3. Population-Level Crop Production and Contextual Indicators

Country-level crop production indicators were obtained from internationally standardized open-access repositories, specifically the World Bank Open Data [16], the Global Health Observatory (World Health Organization) [17], and the Our World in Data [18]. These databases provide harmonized annual estimates of agricultural production volumes that are comparable across countries and time. In the case of the World Health Organization's Global Health Observatory, data was extracted from health indicators related to nutrition and food security [17].

The primary outcomes consisted of annual production volumes (metric tons) for 23 crop-specific indicators grouped into three agricultural domains: (1) staple crops (cereals, pulses, and oilseeds); (2) horticultural products (fruits, vegetables, and tubers); and (3) commodity and industrial crops (plantation and cash crops). These domains were selected to capture distinct structural segments of global food systems, ranging from subsistence-oriented staples to export-oriented commodities [15]. Production volume was retained as the primary metric to reflect aggregate output performance at the national level.

Indicator selection was guided by three criteria: (a) global relevance in terms of production scale or nutritional contribution; (b) availability of consistent longitudinal data across income groups; and (c) representation of structurally diverse agricultural sectors. All outcomes were extracted at the country-year level covering the period 2000–2025, preserving the complete temporal series when available.

To characterize structural conditions potentially influencing translational dynamics, contextual moderators were retrieved from internationally recognized repositories, including the World Bank Governance Indicators [16], the Global Health Observatory (World Health Organization) [17], and related multilateral datasets [18]. These moderators encompassed institutional stability (e.g., territorial control, corruption indices, administrative quality), health-system capacity (e.g., healthcare access and quality, health researcher density, healthy life expectancy), and selected financial assistance indicators (e.g., official development assistance (ODA) disaggregated by sector). The inclusion of these variables was theory-driven and aimed at representing structural capacity dimensions that may condition the relationship between publication activity and crop production.

All contextual indicators were extracted at the country-year level using the most recent standardized estimates available within the analytical window. When multiple observations existed, the full temporal sequence was retained to preserve longitudinal continuity.

For panel construction, country-level indicators were aggregated by income group and year using population-weighted means, ensuring that estimates reflected population exposure rather than unweighted country averages. Total population within each income-year stratum was calculated as the sum of constituent country populations.

No imputation procedures were applied to missing data. Analyses were conducted using complete-case observations to preserve the integrity of officially reported estimates and avoid introducing additional modeling assumptions into structural effect estimation. Consequently, the effective sample size varied across outcomes and moderator specifications depending on indicator availability, particularly for some contextual variables derived from multilateral sources with non-uniform reporting completeness.

The 23 crop indicators were retained to represent structurally distinct segments of the food system rather than interchangeable measures of a single latent productivity construct. Accordingly, the study was not designed to estimate agronomic productivity in a narrow sense. Yield per hectare, harvested area, climate variability, soil degradation, irrigation, and input intensity were not modelled explicitly; therefore, production volume should be interpreted as an aggregate output measure and not as a direct efficiency metric.

2.4. Statistical Analysis

2.4.1. Data Aggregation and Construction of the Analytic Panel

An annual analytical panel stratified by World Bank income group was constructed to examine structural co-variation between food-security-related publication activity and crop production performance. Rather than modeling each country independently, the panel was designed at the income-year level to capture macro-structural patterns that characterize groups of economies sharing comparable institutional and developmental profiles [12].

Food-security-related publication activity was quantified as the total number of peer-reviewed publications attributed to each country-year and subsequently aggregated within income-year strata. Country attribution was based on the corresponding author's institutional affiliation, enabling approximation of national research ecosystem activity.

Because crop production and contextual indicators were originally defined at the country-year level, a structured aggregation procedure was implemented to prevent artificial replication of identical national indicators across multiple publications. For each country–income-year stratum, production and moderator variables were preserved alongside total population counts [12].

Aggregation to the income-year level was performed using population-weighted means, ensuring that group-level estimates reflected the distribution of population exposure rather than simple arithmetic averages across countries. Total population within each income-year was computed as the sum of constituent national populations. This weight-

ing strategy aligns with the ecological objective of representing macro-level structural environments in which both scientific ecosystems and agricultural systems operate.

The resulting income-year dataset integrated three core components: (a) production activity measures; (b) crop production indicators; and (c) contextual structural moderators. This merged panel constituted the analytical foundation for all subsequent modeling stages.

The final analytic dataset comprised 23 crop production indicators grouped into three agricultural domains: Staple crops (n = 8); Horticulture (n = 8); and Commodity and Industrial crops (n = 7). All production outcomes were expressed in metric tons (t), preserving comparability across time and income strata.

Aggregation to the income-group-by-year level was deliberate and theory-driven. The objective was not to estimate within-country causal effects, but to examine macro-structural co-variation across development strata characterized by broadly comparable economic and institutional conditions. Population-weighted means were used to reduce the influence of small-country volatility and to reflect group-level exposure more faithfully. However, this approach cannot eliminate substantial heterogeneity within income categories and may partially reflect the influence of large agricultural producers; this trade-off is addressed explicitly in the Discussion.

2.4.2. Step 1: Stratified Two-Variable Regression Models

The first analytical stage explored the direction and magnitude of the association between food-security-related publication activity and each crop production indicator within income strata. For each outcome, income-stratified regression models of the form production outcome ~ publication activity were estimated using complete-case data, retaining only strata with at least eight observations.

To ensure comparability, a single model specification per indicator was selected based on pooled data and applied consistently across income groups. Model choice was guided by the empirical distribution of each outcome. Given that production indicators were expressed in metric tons, Gaussian linear regression was the default approach, with log-transformed Gaussian models applied to strongly right-skewed variables. Alternative specifications were used only when distributional properties required them.

Robust variance estimators were implemented to account for heteroskedasticity and potential temporal autocorrelation. When available, heteroskedasticity- and autocorrelation-consistent (HAC) standard errors were used; otherwise, HC3 robust standard errors were applied. Wald 95% confidence intervals were computed for all estimates.

For linear models, coefficients (β) represent the absolute change in production (metric tons) associated with one additional publication. For log-linear models, effects were expressed as multiplicative ratios (exp(β)). Ratio-based results were additionally rescaled to represent the expected change associated with 100 additional publications, solely for interpretative clarity (Supplementary Material File S1).

Step 1 was conceived as an exploratory screening stage intended to characterize the raw direction, magnitude, and heterogeneity of bivariate associations across crop domains and income strata. It was not intended to serve as the main adjusted inferential model. For this reason, agronomic covariates such as harvested area, climatic variability, or input intensity were not incorporated at this stage. The principal inferential emphasis of the manuscript rests on the hierarchical models and moderator analyses presented in Steps 2 and 3.

2.4.3. Step 2: Hierarchical (Mixed-Effects) Panel Models

To account for the longitudinal and clustered structure of the data, associations identified in Step 1 were re-estimated using hierarchical mixed-effects panel models. This

approach allowed us to model repeated observations over time within income groups while accounting for between-group heterogeneity.

Models were fitted when sufficient data were available ($\geq$20 observations overall and $\geq$2 income groups). For each crop indicator, mixed-effects models were specified with publication activity as a fixed effect and publication year (centered) to capture secular trends. Income group was incorporated as a random effect to account for structural differences across development strata. A random intercept was included by default, and random slopes for publication activity were evaluated when supported by the data.

Because the final analytic panel was constructed at the income-group-by-year level, country fixed effects were not estimable within the aggregated framework. The inclusion of income group as a random effect was therefore intended to capture between-stratum structural heterogeneity while preserving the macro-level focus of the analysis.

Outcome distributions were handled using the same principles applied in Step 1. Gaussian mixed-effects models were used for production volumes on the original scale, whereas log-transformed specifications were applied to strongly right-skewed outcomes to stabilize variance [19]. For bounded indicators, appropriate generalized mixed-effects formulations were employed.

Fixed-effect estimates for publication activity were extracted with robust inference, and results were reported on interpretable scales consistent with the model link (absolute changes in metric tons or multiplicative ratios). To address multiplicity across indicators, statistical significance was evaluated using the Benjamini–Hochberg FDR procedure [20].

For ease of interpretation, ratio-based estimates were additionally expressed as the expected change associated with 100 additional publications. Full model specifications and diagnostics are provided in Supplementary Material File S2.

2.4.4. Step 3: Mixed-Effects Moderator Screening

The third analytical stage examined whether structural conditions modify the association between publication activity and crop production. Moderation was evaluated by introducing interaction terms between publication activity and pre-specified contextual variables within mixed-effects panel models of the form: production outcome ~ publication activity + moderator + (publication activity $\times$ moderator) + year + (1 | income group).

Candidate moderators were defined a priori based on the conceptual framework of structural capacity and organized into six theory-driven clusters (Supplementary Material File S3). Only variables distinct from both the outcome and the primary exposure were considered. Models were estimated when sufficient variability and sample size were available ($\geq$25 observations and $\geq$2 income groups).

All continuous predictors were mean-centered to mitigate collinearity. Random slopes were not included at this stage to preserve model stability and comparability across the large number of interaction tests performed.

Distributional assumptions followed the specifications applied in Step 2. The primary parameter of interest was the interaction coefficient, which quantifies whether the association between publication activity and production differs across levels of the moderator. Estimates were reported on interpretable scales consistent with the model link, accompanied by Wald 95% confidence intervals.

The interaction coefficient was interpreted strictly as an effect-modification parameter, that is, as the change in the slope linking publication activity and crop production across levels of the moderator. It was not interpreted as a direct marginal production gain attributable to publications alone. For substantive interpretation, conditional effects of publication activity were estimated at the 25th and 75th percentiles of each moderator,

allowing the reader to evaluate whether the association was attenuated, amplified, or directionally reversed across structural contexts.

For ratio-based models, effects were additionally expressed as the expected change associated with 100 additional publications. Where appropriate, contrasts between high and low moderator levels were computed to summarize the magnitude of structural modification.

Given the exploratory yet theory-guided nature of this screening stage, control of false discoveries was implemented using the Benjamini–Hochberg FDR procedure applied to interaction *p*-values [20]. False-discovery control was applied within this analytical step because the interaction models constitute a distinct inferential family relative to the exploratory screening and the main mixed-effects models. Full model results are reported in Supplementary Material File S3.

The complete annotated R script and supplementary data are publicly available to ensure reproducibility and transparency (https://doi.org/10.5281/zenodo.18298032).

3. Results

3.1. Publication Activity and Crop Production Patterns Across Income Groups

Across the 23 crop production indicators examined, spanning staple, horticultural, and commodity/industrial sectors, 92 income-specific models were estimated in the stratified analysis. Of these, 67 associations reached nominal statistical significance ($p < 0.05$), with significant estimates distributed across all income strata: HICs ($n = 19$), LMICs ($n = 19$), LICs ($n = 15$), and UMICs ($n = 14$).

Overall, 59 of the 92 estimates were negative, indicating that increases in food-security-related publication activity were frequently accompanied by stable or declining production volumes in several structural settings. However, the sign and magnitude of the associations varied substantially across crop domains and income groups, underscoring the heterogeneous and context-dependent character of the observed patterns rather than supporting a uniform productivity effect (Figure 1; Supplementary Material File S1).

3.2. Staple Crop Production (Cereals and Pulses/Oilseeds)

Within the staple-crop domain, associations between food-security-related publication activity and production volumes exhibited marked heterogeneity across income settings, with a predominance of negative estimates but notable context-specific deviations.

Barley production showed statistically significant declines in LICs (β = −3262.40 t; 95% CI −4096.92 to −2427.89; $p < 0.001$), LMICs (β = −303.54 t; 95% CI −479.28 to −127.79; $p = 0.0024$), and HICs (β = −576.34 t; 95% CI −962.31 to −190.38; $p = 0.0074$), suggesting that in several structural contexts, increases in publication activity coincided with reduced volumetric output. A similar directional pattern emerged for bean production, where negative estimates were observed across all income groups: LMICs (β = −965.87 t; 95% CI −1534.36 to −397.38; $p = 0.0028$), LICs (β = −448.68 t; $p < 0.001$), UMICs (β = −120.92 t; $p < 0.001$), and HICs (β = −103.64 t; $p < 0.001$). Wheat production followed this trend in LMICs (β = −18,146.64 t; 95% CI −28,116.56 to −8176.72; $p = 0.0016$), UMICs (β = −7985.23 t; $p = 0.0074$), and HICs (β = −2458.44 t; $p = 0.0028$).

In contrast, soybean production demonstrated differentiated trajectories. Negative estimates were observed in HICs (β = −3709.20 t; $p < 0.001$) and LMICs (β = −2366.62 t; $p = 0.0016$), whereas LICs exhibited a significant positive association (β = 1703.43 t; 95% CI 640.66 to 2766.20; $p = 0.0044$), indicating that under some structural conditions publication growth paralleled volumetric expansion. Sesame seed production also displayed divergence: positive estimates in LICs (β = 1256.07 t; $p < 0.001$) and HICs (β = 4.41 t; $p = 0.0046$) contrasted with a negative estimate in LMICs (β = −36.18 t; $p = 0.043$), further highlighting crop-specific variability across development strata.

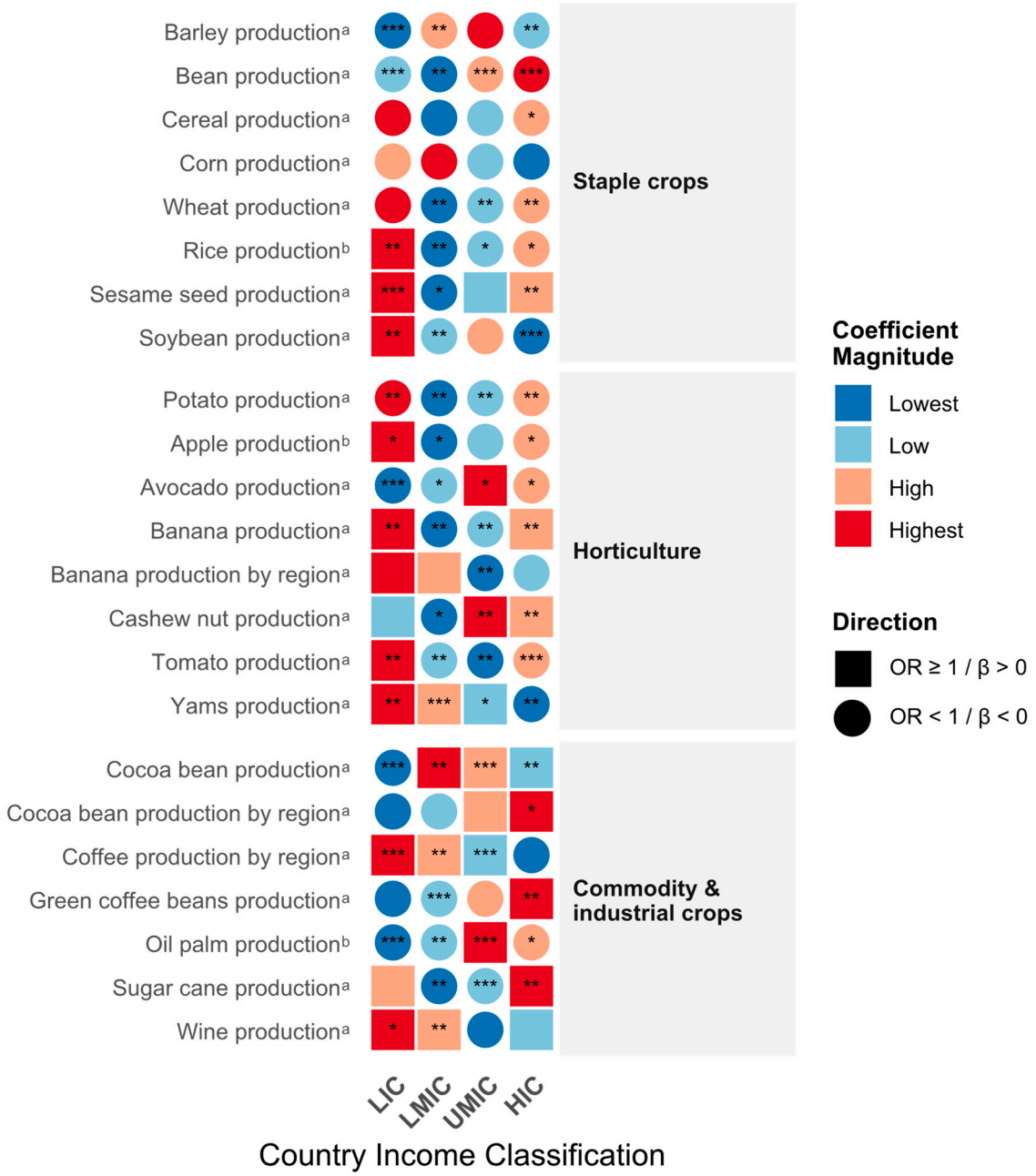


Figure 1. Food security-related publications and crop-production indicators across income groups. The heatmap summarizes regression estimates linking food-security-related publication activity to 23 crop-production indicators grouped into three domains: (1) Staple crops, (2) Horticulture and (3) Commodity and industrial crops. Countries are grouped by World Bank income classification (Low-Income Countries (LIC), Lower-Middle-Income Countries (LMIC), Upper-Middle-Income Countries (UMIC), High-Income Countries (HIC); *x*-axis). Color encodes the within-indicator rank of the point estimate (Lowest → Highest) across income groups. Shape indicates effect direction: squares = positive associations; circles = negative associations. Model superscripts denote the regression family and effect unit reported for each indicator: [a] Linear Gaussian (β) and [b] Log-linear Gaussian with log-transformed outcome (reported as a multiplicative ratio, exp(β)). Statistical significance is indicated by stars (* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$).

Rice production, modeled on the multiplicative scale, underscored this heterogeneity. For each 100 additional publications, production increased substantially in LICs by 36.26% (95% CI 11.97% to 65.81%; $p = 0.005$), whereas modest proportional declines were observed in LMICs (−4.34%; 95% CI −7.26% to −1.34%;

p = 0.009), HICs (−2.07%; p = 0.011), and UMICs (−2.15%; p = 0.035). Aggregate cereal production was significantly negative only in HICs (β = −15,627.40 t; p = 0.049). Collectively, these findings indicate that staple-crop production did not respond uniformly to increases in publication activity across income contexts, but instead followed crop-specific and structurally differentiated trajectories.

3.3. Horticultural Production (Fruits, Vegetables and Tubers)

Within the horticultural domain, patterns differed notably between tuber crops and fruit-producing sectors, again revealing pronounced income-stratified variability.

Tuber production exhibited predominantly negative estimates across income settings. Potato output declined significantly in LMICs (β = −9684.19 t; p = 0.0012), UMICs (β = −6591.53 t; p = 0.0057), HICs (β = −1306.38 t; p = 0.0016), and LICs (β = −993.52 t; p = 0.0057). Tomato production followed a similar configuration, with significant decreases in UMICs (β = −5034.86 t; p = 0.0053), LMICs (β = −2526.06 t; p = 0.0036), and HICs (β = −644.99 t; p < 0.001), whereas LICs displayed a modest but statistically significant increase (β = 228.44 t; p = 0.0033).

Fruit crops demonstrated greater directional heterogeneity. Banana production expanded in LICs (β = 7194.19 t; p = 0.0057) and HICs (β = 264.00 t; p = 0.0045), yet contracted in LMICs (β = −5308.15 t; p = 0.0019) and UMICs (β = −742.64 t; p = 0.0013). Yam production showed substantial positive estimates in LICs (β = 49,127.03 t; p = 0.0015) and LMICs (β = 3145.63 t; p < 0.001), alongside a smaller increase in UMICs (β = 543.43 t; p = 0.047), suggesting that certain root crops may follow distinct structural trajectories. Avocado production displayed an income-differentiated configuration: negative estimates in LICs (β = −138.61 t; p < 0.001), LMICs (β = −14.92 t; p = 0.012), and HICs (β = −5.34 t; p = 0.019) contrasted with a positive estimate in UMICs (β = 21.12 t; p = 0.029). Cashew nut production similarly varied, increasing in UMICs (β = 153.03 t; p = 0.0011) and HICs (β = 126.30 t; p = 0.0054), while declining in LMICs (β = −33.21 t; p = 0.021).

Apple production, modeled on the multiplicative scale, further illustrated this divergence. For every 100 additional publications, production increased markedly in LICs by 94.40% (95% CI 22.30% to 209.00%; p = 0.01), whereas proportional reductions were observed in LMICs (−3.00%; p = 0.011) and HICs (−1.52%; p = 0.03). Overall, horticultural production did not conform to a common directional pattern. Instead, crop-specific and income-dependent configurations predominated, reinforcing the structurally heterogeneous character of the publication-production relationship.

3.4. Commodity and Industrial Crop Production (Plantation and Cash Crops)

Production patterns within commodity and industrial crops also displayed pronounced income-dependent divergence, particularly in sectors closely integrated into global value chains.

Cocoa bean production declined in LICs (β = −2164.24 t; p < 0.001), whereas positive estimates were observed in LMICs (β = 294.55 t; p = 0.0047), UMICs (β = 216.71 t; p < 0.001), and HICs (β = 181.09 t; p = 0.002), indicating contrasting trajectories across structural contexts. Coffee production demonstrated a broadly positive configuration in LICs (β = 3172.59 t; p < 0.001), LMICs (β = 507.16 t; p = 0.0031), and UMICs (β = 235.39 t; p < 0.001). In contrast, green coffee bean output declined in LMICs (β = −28.15 t; p < 0.001) while increasing in HICs (β = 43.75 t; p = 0.0043), underscoring differentiation even within closely related commodity categories.

Oil palm production, modeled on the multiplicative scale, further illustrated structural heterogeneity. For every 100 additional publications, production increased in UMICs by 2.45% (95% CI 1.41% to 3.49%; p < 0.001), whereas proportional declines were observed

in LICs (−5.81%; $p < 0.001$), LMICs (−2.24%; $p = 0.0074$), and HICs (−1.40%; $p = 0.0125$). Sugar cane production showed substantial negative estimates in LMICs (β = −76,801.45 t; $p = 0.0018$) and UMICs (β = −15,784.90 t; $p < 0.001$), contrasted by a positive estimate in HICs (β = 5729.55 t; $p = 0.0042$). Wine production increased in LICs (β = 833.23 t; $p = 0.0118$) and LMICs (β = 121.04 t; $p = 0.0017$). Taken together, commodity and industrial crops exhibited no consistent directional pattern, suggesting that publication activity and production volume do not align uniformly within globally integrated food sectors.

3.5. Hierarchical Mixed-Effects Models

Following the income-stratified analyses, hierarchical mixed-effects models were used to re-estimate associations while accounting for temporal structure, between-income heterogeneity, and multiplicity. When the data were modeled within this multilevel framework and adjusted for FDR, the number of statistically significant associations decreased substantially. Only five crop indicators retained significance after multilevel adjustment and correction, corresponding to a small subset of the nominally significant findings observed in the stratified screening stage.

Among the indicators that remained significant, cereal production showed a decrease of 43,379.33 tons (95% CI −58,709.09 to −28,049.57; padj < 0.001) per additional unit of publication activity, and corn production demonstrated a similar configuration, with an estimated reduction of 26,312.05 tons (95% CI −34,303.28 to −18,320.83; padj < 0.001). Among outcomes modeled on the multiplicative scale, rice production showed a proportional decline of 3.92% per 100 additional publications (95% CI −5.83% to −1.00%; padj = 0.01). Within the horticultural domain, apple production decreased by 4.88% per 100 publications (95% CI −8.61% to −1.00%; padj = 0.041), while banana production by region declined by 3211.73 tons (95% CI −5538.15 to −885.31; padj = 0.041).

In contrast, no statistically significant associations were observed for commodity and industrial crops after multilevel adjustment. Indicators such as cocoa bean, coffee, and oil palm production did not retain significance within the hierarchical framework. Overall, the predominance of non-significant estimates after hierarchical adjustment indicates that many of the nominal associations identified in the stratified models were not stable once temporal and between-income dependencies were explicitly modeled. For that reason, the mixed-effects results were prioritized in the substantive interpretation of the study (Figure 2; Supplementary Material File S2).

Given the marked attenuation of nominal associations after multilevel adjustment, the next step examined whether selected structural indicators modified the conditional slope linking food security-related publication activity and crop production across domains.

3.6. Potential Sources of Heterogeneity

3.6.1. Governance and State Capacity as Moderators

Governance-related indicators substantially modified the association between food-security-related publication activity and crop production, indicating that institutional conditions shape how knowledge-generation environments align with agricultural output. Across several crop domains, the conditional slope linking publication activity to production became less negative, or even changed sign, at higher levels of state capacity and governance quality (Table 1).

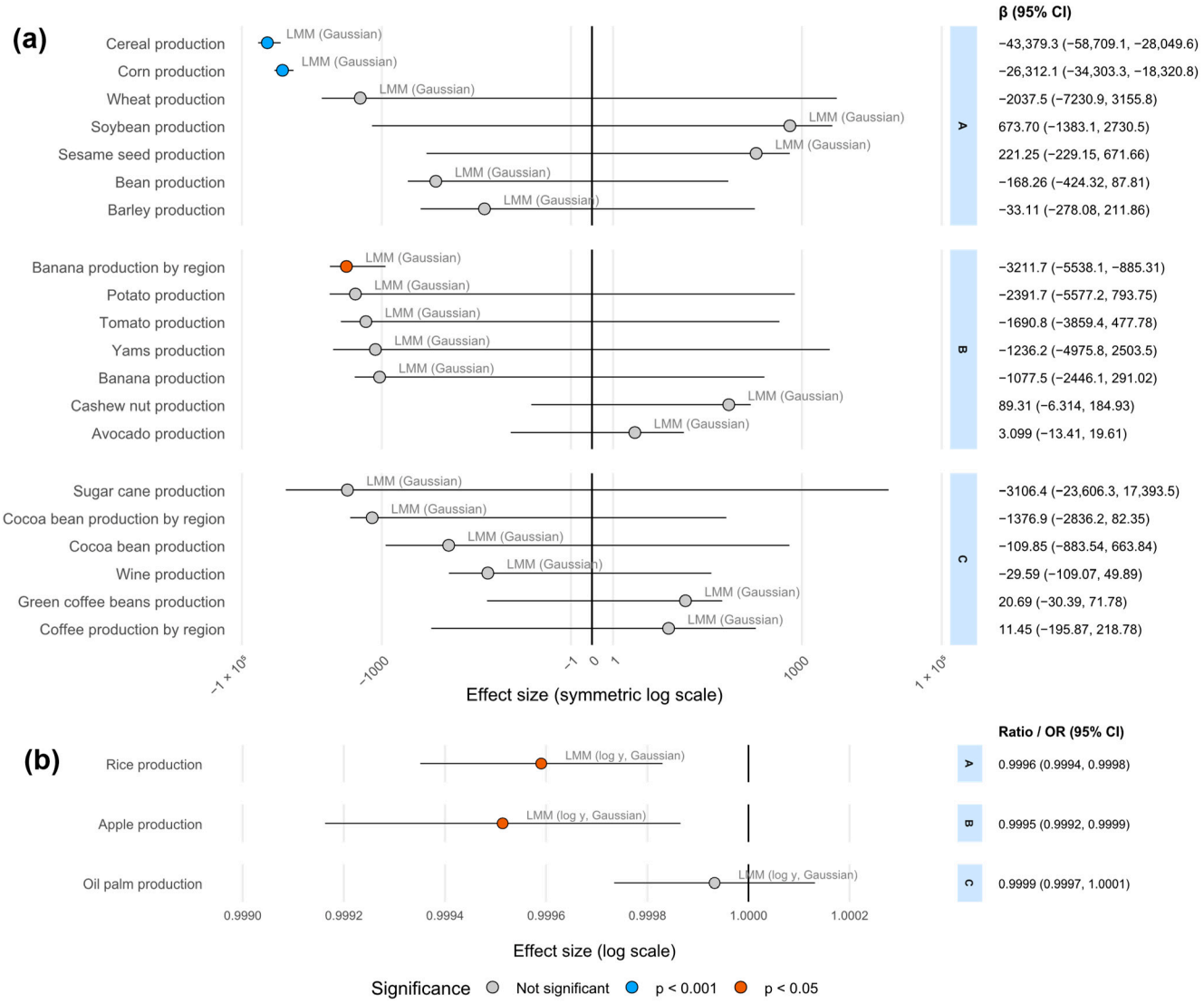


Figure 2. Forest plot of associations between publication activity and global crop indicators. Estimates were derived from linear mixed-effects models (LMM) assessing the relationship between food security-related publication activity and various crop production outcomes. (**a**) Beta coefficients (β) for the three agricultural domains, displayed on a symmetric logarithmic scale to visualize positive and negative effects of varying magnitudes; the vertical reference line at 0 indicates a null effect. (**b**) Ratios for specific products (Rice, Apple, and Oil palm), presented on a logarithmic scale with a vertical reference line at 1. In this panel, letter codes indicate the overarching categories for each product (A: Staple crops; B: Horticulture; C: Commodity/industrial crops). In both panels, points represent the estimated effect size, and horizontal lines denote 95% confidence intervals (95% CI). Point fill color reflects statistical significance based on *p*-values adjusted using the Benjamini–Hochberg method: blue (padj < 0.001), orange (padj < 0.05), and grey (not significant). The model type and distribution family are specified next to each estimate. The right-hand panel reports the precise numerical values for the coefficients or ratios with their respective 95% CIs.

Table 1. Mixed-effects interaction models assessing structural moderators of the association between food security-related publication activity and global crop outcomes.

Moderator (Z)	Model Family	Interaction Effect	95% CI	P25 Slope	P75 Slope	FDR *p*-Value
Avocado production						
Official development assistance for medical research and basic health sectors per capita, by income	Gaussian (identity)	−32.20	−50.01–−14.58	−5.05	−60.12	0.004
Banana production						
Health Access & Quality	Gaussian (identity)	166	103.42–229.11	−7569	−1616	<0.001
Percentage of territory effectively controlled by government	Gaussian (identity)	46,831	24,721–68,941	−3759	571.07	<0.001
Barley production						
Rigorous and impartial public administration index	Gaussian (identity)	−342.24	−453.05–−231.44	253.57	37.24	<0.001
Bean production						
Healthy life expectancy	Gaussian (identity)	87.64	59.78–118.49	−1015	25.44	<0.001
Percentage of territory effectively controlled by government	Gaussian (identity)	8285	4825–11,745	−611.46	154.7	<0.001
Official development assistance for medical research and basic health sectors per capita, by region	Gaussian (identity)	−643.77	−819.42–−468.13	42.53	−1116	<0.001
Potato production						
Percentage of territory effectively controlled by government	Gaussian (identity)	126,105	79,126–173,084	−126,677	−1016	<0.001
Soybean production						
Political corruption index	Gaussian (identity)	6024	2672–9377	−48.92	821.74	0.004
Wheat production						
Percentage of territory effectively controlled by government	Gaussian (identity)	175,489	103,911–246,987	−16,703	−476.51	<0.001
Sugar cane production						
Healthy life expectancy	Gaussian (identity)	6892	4407–9376	−79,200	2676	<0.001
Health researchers (in full-time equivalent) per million inhabitants, by region	Gaussian (identity)	353.52	222.95–484.09	−27,481	1378	<0.001
Healthcare access and quality	Gaussian (identity)	2455	1543–3366	−104,161	−16,265	<0.001

Table 1. *Cont.*

Moderator (Z)	Model Family	Interaction Effect	95% CI	P25 Slope	P75 Slope	FDR *p*-Value
Oil palm production						
Official development assistance for medical research and basic health sectors per capita, by income	Gaussian (log y) *	0.97	0.95–0.98	1.01	0.95	<0.001
Political corruption index	Gaussian (log y) *	1.06	1.03–1.10	1.015	1.024	0.006
Coffee production						
Political corruption index	Gaussian (identity)	713.78	456.54–971.01	26.88	130.03	<0.001

Interaction coefficients represent effect modification and should not be interpreted as direct production gains per publication. Substantive interpretation should rely on the conditional slopes estimated at the 25th (P25) and 75th (P75) percentiles of each moderator. * Ratios per 100 additional publications. FDR-adjusted *p*-values are reported in their original format.

Territorial sovereignty emerged as one of the most influential moderators. For wheat production, the interaction term indicated that the slope relating publication activity to output increased by 175,489 tons for each unit rise in the proportion of territory effectively controlled by government (95% CI 103,911 to 246,987; padj < 0.001). When conditional effects were estimated across the moderator distribution, the association was strongly negative at the 25th percentile of territorial control (P25 slope = −16,703 tons per publication) but markedly attenuated at the 75th percentile (P75 slope = −476.51 tons).

A comparable pattern was observed for potato production, for which the interaction coefficient was 126,105 (95% CI 79,126 to 173,084; padj < 0.001), with the conditional slope shifting from strongly negative at lower territorial control (P25 = −126,677) to near null at higher control (P75 = −1016). Banana production showed an even clearer directional change: the interaction coefficient was 46,831 (95% CI 24,721 to 68,941; padj < 0.001), and the conditional association moved from negative at the 25th percentile (P25 = −3759) to positive at the 75th percentile (P75 = 571.07). These patterns suggest that stronger territorial control attenuates, and in some cases reverses, the negative association between publication activity and crop output.

Corruption-related measures and administrative quality further differentiated the conditional slopes. For soybean production, the political corruption index showed an interaction coefficient of 6024 (95% CI 2672 to 9377; padj = 0.004). At the lower end of the moderator distribution, the conditional slope was slightly negative (P25 = −48.92), whereas at the upper percentile it became strongly positive (P75 = 821.74), indicating a marked shift in the direction and magnitude of the association across governance contexts. Coffee production showed a similar pattern, with an interaction coefficient of 713.78 (95% CI 456.54 to 971.01; padj < 0.001), and conditional slopes increasing from 26.88 at the 25th percentile to 130.03 at the 75th percentile.

By contrast, for barley production, the rigorous and impartial public administration index was associated with a smaller positive slope as the moderator increased (interaction coefficient = −342.24; 95% CI −453.05 to −231.44; padj < 0.001), with conditional effects declining from 253.57 at P25 to 37.24 at P75.

Taken together, these findings indicate that governance does not simply correlate with production levels; rather, it modifies the slope linking publication activity and production,

often attenuating negative conditional associations or shifting them toward more favorable configurations under stronger institutional conditions.

3.6.2. Research System and Health Context as Moderators

Indicators reflecting health-system capacity and research workforce density also modified the association between food security-related publication activity and agricultural output, underscoring that crop performance is embedded within broader institutional and human-capital environments (Table 1).

For sugar cane production, health researchers (in full-time equivalent) per million inhabitants showed a strong interaction coefficient of 353.52 (95% CI 222.95 to 484.09; padj < 0.001). The conditional slope was markedly negative at lower researcher density (P25 = −27,481), but became positive at higher density (P75 = 1378), indicating a clear reversal in the direction of the association across the moderator distribution. Healthy life expectancy showed a similar pattern for the same crop, with an interaction coefficient of 6892 (95% CI 4407 to 9376; padj < 0.001), and conditional slopes changing from strongly negative at the 25th percentile (P25 = −79,200) to positive at the 75th percentile (P75 = 2676). Healthcare access and quality also modified sugar cane production, with an interaction coefficient of 2455 (95% CI 1543 to 3366; padj < 0.001), attenuating the negative conditional slope from −104,161 at P25 to −16,265 at P75. Together, these results indicate that stronger health-system and research-capacity conditions can substantially weaken, and in some cases reverse, negative publication–production associations.

Comparable patterns were observed in other crops. For bean production, healthy life expectancy yielded an interaction coefficient of 87.64 (95% CI 59.78 to 118.49; padj < 0.001), with the conditional slope moving from negative at lower life expectancy (P25 = −1015) to slightly positive at higher life expectancy (P75 = 25.44). Banana production showed moderation by healthcare access and quality, with an interaction coefficient of 166.00 (95% CI 103.42 to 229.11; padj < 0.001), attenuating the negative slope from −7569 at the 25th percentile to −1616 at the 75th percentile.

These gradients support the interpretation that health-system resilience and research workforce capacity act as structural conditions that shape whether publication activity aligns with more favorable crop-output trajectories. Rather than indicating direct agricultural effects of health variables themselves, these moderator patterns likely capture broader differences in social robustness, human capital, and institutional capability that condition the translation of knowledge into production environments.

3.6.3. Financial Assistance as Structural Moderators

Indicators reflecting external financial flows also modified the association between food-security-related publication activity and selected crop outcomes, suggesting that funding environments interact with domestic structural conditions rather than operating independently of them (Table 1).

For oil palm production, ODA for medical research and basic health sectors per capita, by income, showed an interaction ratio of 0.97 (95% CI 0.95 to 0.98; padj < 0.001). Because this outcome was modeled on the multiplicative scale, substantive interpretation relies on the conditional ratios: at the 25th percentile of ODA, the association between publication activity and output corresponded to a slight positive change (P25 = 1.01), whereas at the 75th percentile it shifted toward a negative proportional association (P75 = 0.95). Thus, higher levels of this financial indicator were associated with a less favorable conditional relationship between publication activity and oil palm production.

A comparable gradient was observed for avocado production. ODA for medical research and basic health sectors per capita, by income, showed an interaction coefficient

of −32.20 (95% CI −50.01 to −14.58; padj = 0.004), with the conditional slope becoming more negative as the moderator increased, from −5.05 at the 25th percentile to −60.12 at the 75th percentile. Bean production showed a similar pattern for ODA by region, with an interaction coefficient of −643.77 (95% CI −819.42 to −468.13; padj < 0.001), and conditional slopes shifting from 42.53 at P25 to −1116 at P75. These findings indicate that external financial flows can alter both the magnitude and direction of the conditional publication–production association. Rather than implying that financial assistance directly suppresses agricultural output, these results more plausibly suggest that such flows are embedded in broader structural environments, potentially including sectoral reorientation, dependency patterns, or investment priorities outside immediate volumetric crop expansion—that shape how publication activity co-evolves with production.

4. Discussion

The principal finding of this study is that the association between food security-related publication activity and crop production is structurally heterogeneous, non-linear, and not consistently directed across income settings [6,9]. The marked attenuation of statistically significant associations after hierarchical mixed-effects modelling and FDR correction suggests that a substantial proportion of the variation observed in stratified analyses reflects contextual heterogeneity and clustered temporal structure rather than stable cross-context effects [12,13,20].

Accordingly, the results do not support a universal interpretation in which growth in publication activity is expected to translate proportionally or consistently into higher agricultural output across crops and development strata [6–9].

The predominance of negative associations, particularly in several high-income settings, should not be interpreted as evidence that research activity suppresses crop production. A more plausible interpretation is that, in structurally mature systems, publication growth may coincide with diversification, technological intensification, environmental regulation, crop substitution, or shifts toward higher-value and quality-oriented agricultural sectors rather than simple expansion in tonnage [7,10,11]. From this perspective, the observed decoupling between publication activity and volumetric output may reflect structural transformation in agricultural systems rather than inefficiency of research ecosystems per se [7,10].

This interpretation is also consistent with the broader idea that bibliometric expansion is, at best, an indirect indicator of knowledge generation rather than a direct measure of technological adoption, implementation, or innovation performance [5,7,21,22]. Publications may reflect the activity of research systems, but they do not directly capture whether knowledge reaches producers, is embedded into extension systems, informs input use, or becomes operational through institutional and policy mechanisms capable of affecting production outcomes [6,7,9,23]. Accordingly, the present findings point less to a failure of research itself than to a translational problem: knowledge generation and agricultural performance appear to be linked through implementation pathways that vary substantially across structural environments [7,8,21–24].

The moderator analyses reinforce this interpretation. Territorial control, corruption-related indicators, and administrative quality modified the conditional slopes linking publication activity and crop output, in several cases attenuating negative associations or shifting them toward more favorable configurations across the moderator distribution [7]. These patterns suggest that governance does not merely coexist with agricultural performance; rather, it conditions whether research ecosystems can be translated into production-relevant processes through policy continuity, administrative reliability, land and territorial governance, and the coordination of infrastructure and supply-chain functions [2–4,7]. In this

sense, structural capacity appears to operate as translational infrastructure within food systems [2,7,23].

Health system and research capacity indicators also played an important moderating role. Researcher density, healthy life expectancy, and healthcare access and quality modified several crop-specific associations, in some cases shifting conditional slopes from strongly negative to positive [25]. Although these variables are not agricultural inputs in a narrow agronomic sense, they likely capture broader dimensions of human capital resilience, labor stability, institutional capability, and state functionality that shape the environment in which knowledge can be absorbed and operationalized [25]. The findings therefore support a systems-level view in which agricultural performance is embedded within wider socio-institutional and health infrastructures rather than determined solely by agronomic inputs or publication volume [7,25].

External financial flows showed similarly differentiated patterns. The moderation effects observed for ODA should not be interpreted as evidence that financial assistance directly reduces production. Rather, they likely reflect the fact that external funding is embedded in complex structural environments, including dependency configurations, targeted spending priorities, sectoral reorientation, and investments that may not translate into immediate volumetric crop expansion [26]. In this regard, the results align with the broader observation that the size or visibility of a research system is not equivalent to its translational effectiveness, and that innovation capacity depends not only on resources, but also on how those resources are organized, coordinated, and connected to food-system development [7,8,26].

An additional issue is temporal lag. The effects of agricultural research often emerge over medium- to long-term horizons through breeding cycles, institutional learning, technology transfer, extension processes, and delayed adoption at the field level [6,7,10]. Because the present analyses primarily capture contemporaneous structural co-variation, they may underestimate or misalign research effects that materialize only after several years. This is particularly relevant in food systems, where the path from knowledge production to implementation is frequently discontinuous and mediated by organizational and regulatory bottlenecks [6,7,9,21–24]. Future studies should therefore explore lagged specifications and distributed temporal effects to distinguish short-term decoupling from delayed translation [7,10].

Several unmodeled factors may also have influenced both publication activity and production volume. Climate variability, soil degradation, harvested area, irrigation, fertilizer and pesticide use, mechanization, and changes in crop composition can affect production trajectories while also shaping research agendas [1,11,27]. Because these variables were not explicitly modeled, residual confounding remains possible, and the results should not be interpreted as direct productivity effects attributable to publications alone [1,22]. This limitation is particularly important given that production volume, although useful as an aggregate output measure, does not capture yield per hectare, technical efficiency, sustainability performance, or product quality [12,22,27].

The aggregation strategy also requires careful interpretation. Grouping observations by World Bank income category enabled the study to evaluate macro-structural patterns across development strata, but this approach cannot eliminate substantial heterogeneity within income groups [14]. Countries within the same income category may differ sharply in agroecology, agricultural specialization, export orientation, institutional capacity, and exposure to climatic and geopolitical risks. Moreover, large agricultural producers may disproportionately shape group-level averages. Thus, the aggregated design should be understood as a deliberate trade-off: it strengthens structural comparability at the macro level while reducing resolution with respect to within-group diversity [12,14].

From a policy perspective, the findings suggest that publication growth alone is a weak basis for evaluating agricultural research performance [7,8,21,22]. Investments in research are more likely to align with productive outcomes when they are accompanied by extension capacity, implementation mechanisms, governance reliability, rural infrastructure, and cross-sector coordination [6,7,21–24]. For governments and funding agencies, this implies that research financing should not be assessed only through bibliometric expansion, but also through the absorptive capacity of institutions and the existence of mechanisms that facilitate the translation of knowledge into agricultural practice [7,8,21–24]. At the global level, evaluative frameworks would benefit from integrating publication activity with indicators of extension functionality, innovation uptake, and agronomic efficiency [8,11,27].

Several limitations should be acknowledged. First, the ecological and income-stratified design precludes causal inference and does not capture within-country heterogeneity. Second, the bibliometric exposure captures a thematically bounded segment of research activity related to food security and healthy food access/availability and therefore should not be interpreted as an exhaustive measure of all agricultural R&D [5,7]. Third, the use of Scopus alone, while methodologically coherent and sufficiently comprehensive for the study objective, may have omitted relevant records indexed in other major or regional databases. Fourth, production volume does not capture yield, efficiency, sustainability, or quality differentiation [11,15,27]. Fifth, complete-case analysis may have affected precision unevenly across models, particularly for contextual moderators with less complete reporting. Sixth, FDR control was applied within analytical families rather than across the full modelling program; a fully global correction would therefore have been more conservative [20].

Notwithstanding these constraints, this study provides, to our knowledge, one of the first multilevel examinations of how food-security-related publication activity co-evolves with crop production within structurally heterogeneous global food systems [7,8].

By integrating bibliometrics with governance, health, and financial moderators, the analysis advances a meta-research perspective on agricultural research performance: it shifts the evaluative lens from output quantity to translational alignment [8,21,22,24]. The findings suggest that future research should move beyond counting publications toward measuring absorptive capacity, institutional translation mechanisms, extension-system functionality, and implementation pathways that connect knowledge ecosystems to production systems [8,21–24,27]. In this sense, the contribution of the present study lies not in identifying simple productivity drivers, but in proposing a systems-level framework through which scientific activity can be evaluated as part of broader food-system governance and resilience architectures [7,8,11,21–24].

5. Conclusions

This global multilevel analysis shows that food-security-related publication activity is not uniformly associated with higher crop production across income settings. After hierarchical adjustment and FDR correction, only a small subset of the nominally significant stratified associations remained robust, and the observed relationships were strongly conditioned by governance, health-system, and financial contexts. These findings therefore argue against treating publication growth as a standalone proxy for agricultural progress or innovation performance.

A more plausible interpretation is that research contributes to production only when embedded within structural environments capable of translating knowledge into practice through institutional stability, implementation capacity, agricultural extension, and cross-sector coordination. In this sense, the study supports a systems-level perspective in which food-system performance emerges from the interaction between knowledge generation and structural capacity rather than from bibliometric expansion alone.

From a meta-research and implementation perspective, the present study highlights the need to move beyond bibliometric expansion as a proxy for agricultural progress. Future evaluations of agricultural research should integrate publication activity with indicators of absorptive capacity, extension functionality, innovation uptake, implementation pathways, and agronomic efficiency in order to better capture whether knowledge generation is actually translated into food-system outcomes. By situating food-security-related publication activity within broader structural architectures, this study contributes a systems-level framework for evaluating research performance within contemporary global food systems.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture16090995/s1, File S1: Full results of stratified two-variable regression models. File S2: Full results of hierarchical (mixed-effects) panel models. File S3: Full results of mixed-effects moderator screening.

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Abbreviations

The following abbreviations are used in this manuscript:

FDR	False Discovery Rate
HAC	Heteroskedasticity- and Autocorrelation-Consistent
HIC	High-Income Countries
LIC	Low-Income Countries
LMIC	Low-Middle-Income Countries
ODA	Official Development Assistance
UMIC	Upper-Middle-Income Countries

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