Global Cropland Requirements for Replacing the Defined Nutritional Contribution of Animal-Source Foods

Reconciling Nutritional-Equivalence Accounting, Primary Product Allocation, Feed-Cropland Reallocation, Productivity Constraints, And Integrated-Farming Perspectives

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***Abstract*—Comparisons between animal-source-food (ASF) and plant-food land requirements depend on the functional unit, system boundary, nutritional equivalence rules, treatment of co-products, yield assumptions, and the distinction between annual crop activity and physical land. This study develops a global agricultural land-balance framework for replacing the defined nutritional contribution of existing ASF supply with plant crops. Protein replacement uses amino-acid-specific digestibility logic; calcium, iron, and zinc use nutrient-specific screening bioavailability adjustments; vitamin A is expressed as retinol activity equivalents; and choline is treated as a boundary target with an incremental screening extension. The primary harmonized working basis is 659.366 Mha/year of annual crop activity. A 13.3% system-level post-harvest-loss sensitivity increases this basis to 760.514 Mha/year. Representative GAEZ-informed productivity scenarios of 90%, 70%, and 50% yield capacity produce replacement requirements of 845.016, 1,086.449, and 1,521.029 Mha/year, respectively. After a productivity-adjusted potential feed-cropland reallocation credit, the corresponding net additional annual crop-activity equivalents are 629.216, 918.605, and 1,401.140 Mha/year. These values correspond in scale to approximately 40%, 59%, and 89% of 1,571 Mha of 2023 global cropland, respectively; they are not estimates of physical land conversion. Screening-level blue-water, fertilizer, labour, and greenhouse-gas modules are reported separately from land-use-change carbon debt and phaseout sensitivities. The results demonstrate that nutritional-equivalence accounting can produce land requirements different from product-level life-cycle assessment because the analytical question and functional unit differ. The framework is therefore presented as a complementary systems-accounting approach rather than as evidence that one food-production system is universally superior.**

***Index Terms*—animal-source foods, nutritional equivalence, cropland, DIAAS, bioavailability, Primary Product Allocation, feed-food competition, GAEZ, land-use ratio, integrated farming systems, life-cycle assessment, food-system modelling.**

I. INTRODUCTION

A. Why the Functional Unit Determines the Land Question

Land-use comparisons in food-system research are often presented as if the only relevant variable were hectares per kilogram of food. In reality, the numerator and denominator of the comparison can change simultaneously. A kilogram of milk, a kilogram of grain, a gram of digestible protein and a complete dietary pattern are different functional units. A land result derived for one cannot automatically be transferred to another.

The present study therefore starts from nutritional contribution rather than commodity mass. The central object is not a kilogram of soybean, chickpea, milk or meat; it is the defined nutritional contribution represented by the existing ASF supply. This choice is consequential because animal foods contain combinations of protein, indispensable amino acids, minerals, vitamins and other nutrients that cannot be represented adequately by crude protein alone.

The same principle applies to land. A hectare of pasture, a hectare of rainfed cereal land and a hectare

of irrigated pulse land are not equivalent production units. Their yields, cropping intensity, water requirements, nutrient balances and opportunity costs differ. A robust comparison must therefore keep land quantity and land productivity conceptually separate.

B. Why Existing Global Studies Can Produce Different Answers

Global food-system studies have produced apparently divergent conclusions about land requirements under plant-based dietary change. This is not necessarily evidence that one study is incorrect. It often reflects differences in the land pool being counted.

[20], for example, reported a very large reduction in total agricultural land under a global plant-based scenario because the scenario substantially removed grazing land and reduced feed demand. A nutritional-equivalence calculation can simultaneously generate a large increase in cropland because it asks how much crop production is required to reproduce a specified nutritional supply. The two results can coexist because total agricultural land and cropland are not interchangeable categories.

Land-use-ratio studies add another dimension by evaluating whether land currently used for feed could produce more human-digestible protein if directly cropped. Integrated-farming studies add yet another dimension by evaluating the combined output of crops, livestock, fish, horticulture and recycling flows. The present study therefore treats these literatures as complementary methodological perspectives rather than as mutually exclusive answers.

Global discussion of animal-source foods and plant-based food systems frequently compresses several different analytical questions into a single land-use comparison. Product-level life-cycle assessment (LCA), for example, can compare environmental footprints per kilogram of food product, while land-use-ratio (LUR) analysis asks whether land used for livestock feed could produce more human-digestible protein if directly cropped. Food-system dietary models can instead estimate how a specified dietary pattern changes total land requirement. A nutritional-equivalence agricultural land-balance model asks a different question: if the nutritional contribution currently supplied by ASF were to be replaced by plant crops under an explicitly defined nutritional and agricultural system, how much crop production and cropland would be required? [20] provided one of the most influential global food-footprint comparisons, synthesizing data from thousands of production systems and modelling a global shift toward plant-based diets. Their scenario found a very large reduction in total agricultural land, driven especially by the elimination of pasture and reductions in feed production.

That result is important, but it is not directly interchangeable with a model that holds the existing ASF nutritional contribution constant and constructs a plant-production system to replace it. The two analyses therefore should be interpreted as answering different questions rather than as one being intrinsically correct and the other incorrect [20].

The present study builds on a production-based India-specific PPA framework developed by [22], which distinguished annual gross cropped area from physical land and explicitly allocated crop production according to primary production purpose. It also extends the author's earlier global AR6-based assessment of plant-only versus mixed systems, which incorporated crop yields, irrigation, fertilizer, energy, GHG and nutrient-bioavailability modules [23]. A separate manure-to-biogas assessment provides context for treating livestock-derived energy and nutrient recycling as system modules rather than automatically counting them as negative emissions [21].

The study is deliberately neutral in its framing. It does not recommend a universal dietary transition, nor does it establish that a mixed system is universally superior. Its purpose is to quantify a defined counterfactual production system and to show how results change when the accounting questions, productivity constraint and resource boundary change.

II. RESEARCH QUESTIONS AND ANALYTICAL BOUNDARY

The principal research question is: what annual cropland requirement results when the nutritional contribution represented by current ASF supply is replaced by plant crops under a defined nutritional-equivalence framework, while preserving explicit treatment of protein quality, non-protein nutrient bioavailability, post-harvest loss, crop productivity, feed-cropland reallocation and system boundaries?

Secondary questions are: (i) how sensitive is the result to representative productivity constraints; (ii) how much of the gross replacement requirement can be offset by reallocating feed-associated cropland; (iii) what screening-level blue-water, fertilizer and labour requirements accompany the additional land; (iv) what are the implications of land-use-change carbon debt and a linear livestock phaseout; and (v) why can this result differ substantially from global LCA and LUR studies?

The functional unit is annual global crop activity expressed primarily as million hectares per year of gross cropped/harvested area. Where physical land is relevant, the analysis explicitly distinguishes it from annual crop activity. This distinction follows the methodological logic developed in the India study of [22].

A hectare harvested twice contributes two hectares to gross cropped area but remains one hectare of physical land.

The replacement target is based on existing ASF nutritional supply, not on a newly prescribed population diet or on recommended dietary allowance adequacy. This is a central boundary choice. The model asks how much plant production is needed to reproduce the defined existing ASF nutritional contribution, rather than how much food would be required to satisfy an independent nutritional adequacy standard.

III. CONCEPTUAL FRAMEWORK: WHY DIFFERENT METHODS PRODUCE DIFFERENT LAND RESULTS

Three accounting layers are especially important. First, LCA commonly allocates environmental burdens according to the relationship between production and final food products, including co-products and downstream uses. Second, LUR evaluates the opportunity cost of feed land by estimating the human-digestible protein that could be produced if suitable feed land were instead used for direct food crops [29]. Third, PPA asks why a crop was cultivated in the first place and assigns primary-purpose production accordingly. The present study uses PPA logic for the feed-cropland reallocation module while retaining a separate nutrient-equivalence model for the replacement system.

This distinction is particularly important for crops with multiple outputs. Soybean, for example, can yield both oil and meal. Assigning all soybean land to livestock feed because meal is fed to animals answers an end-use question, whereas asking whether soybean was cultivated primarily because of oil, food, feed, or a combination of market drivers answers a production-purpose question. Neither question is inherently invalid; they are different allocation questions.

The study therefore avoids using a single universal allocation rule. It preserves the methodological identity of each module and prevents a land number produced under one boundary from being presented as though it were the result of another.

Table 1. Comparison of analytical approaches and their relevance to the present study.

Analytical approach	Primary question	Strength	Main limitation for this study
Product-level LCA	What is the environmental footprint per unit of food product?	Comprehensive multi-impact comparison	Does not by itself solve a nutritional-equivalence replacement problem.
LUR	Would direct food cropping on livestock feed land produce more human-digestible protein?	Explicit feed-food opportunity cost and land suitability	Usually system/product specific; not a complete global nutrient replacement model.
PPA	What was the primary production purpose of the crop?	Makes production driver explicit	Requires careful classification of crop-purpose evidence.
Nutritional-equivalence land balance	How much crop production replaces an existing nutritional contribution?	Directly links nutrition to production and land	Highly sensitive to nutrient-quality, yield and diversification specifications.
Integrated farming systems	How can multiple enterprises jointly use land, biomass and nutrients?	Captures internal recycling and multifunctionality	Results are context-specific and not directly comparable with global crop-only scenarios.

IV. DATA SOURCES AND EVIDENCE BASE

The quantitative framework combines FAOSTAT Food Balance Sheets, FAOSTAT Crops and Livestock Products (QCL), FAO/IIASA GAEZ v5, FAO land and land-degradation assessments, livestock-feed literature, global fertilizer and water-footprint sources, protein-quality guidance, food-composition databases, and published literature on land-use change and nutrient recycling. The master workbook contains a consolidated reference index and an evidence register for model inputs.

FAOSTAT QCL provides production, harvested area and yield information. The crop model uses multi-year yield information rather than relying on a single exceptional harvest. The global ASF baseline includes meat, edible offals, milk excluding butter, eggs and fish/seafood, while animal fats and aquatic plants are kept outside the main protein target.

GAEZ v5 is used as an agronomic framing source for yield gaps and attainable productivity. FAO describes GAEZ v5 as a spatially detailed framework combining climate, soil, terrain and crop characteristics, with actual-versus-potential yield information. The present study does not reproduce a global GAEZ optimization; instead, it maps representative productivity cases into a transparent sensitivity analysis. This distinction is essential for interpretation (Food and Agriculture Organization of the United Nations & International Institute for Applied Systems Analysis [FAO/IIASA], 2025).

The literature evidence is used for two different purposes: numerical model inputs and methodological interpretation. Published studies are not treated as independent observations merely because they are relevant to the topic. In particular, reviews are used to contextualize mechanisms and identify evidence rather than being inserted as pseudo-replicated data points.

V. ASF BASELINE AND NUTRITIONAL REPLACEMENT TARGET

The ASF baseline is constructed from FAOSTAT aggregates. The study includes approximately 56.431 Mt protein from meat, 3.171 Mt protein from edible offals, 27.871 Mt protein from milk excluding butter, 9.827 Mt protein from eggs and 16.133 Mt protein from fish/seafood in the broad protein-related baseline. Animal fats are excluded from the protein target, and aquatic plants embedded in broad animal-product aggregates are excluded from the ASF target. The resulting study baseline is approximately 113.433 Mt/year of ASF protein.

Protein replacement is evaluated with amino-acid-specific digestibility logic rather than multiplying crude protein by a universal digestibility coefficient. The FAO reference pattern for people older than three years is used for indispensable amino acids: histidine 16, isoleucine 30, leucine 61, Sulphur amino acids 23, aromatic amino acids 41, threonine 25, tryptophan 6.6 and valine 40 mg/g protein. Lysine is included in the working amino-acid matrix where required by the source data [4].

The evidence registers maps direct human true-ileal digestibility observations where available and uses category-range midpoint proxies where crop- and form-specific evidence is unavailable. For example, chickpea and mung-bean digestibility evidence comes from human studies, faba bean from human protein-quality work, and soy evidence is available for specific protein forms. These proxies are explicitly classified as screening evidence rather than as universal crop-specific measurements.

Non-protein nutrients are treated separately. Calcium, iron and zinc use nutrient-specific screening bioavailability adjustments; vitamin A is represented using retinol activity equivalents; and choline is retained as a boundary target but remains an incremental screening extension rather than a fully integrated component of the headline 659.366 Mha/year optimization. Calories are excluded from the optimization because the study is designed as a nutrient-equivalence model rather than a caloric food-balance model. Vitamin B12, vitamin D, iodine and long-chain omega-3 sources remain outside ordinary cropland optimization because a crop-only land balance cannot credibly guarantee their complete replacement without fortification, supplementation or external inputs.

Table 2. Treatment of nutritional components within the replacement framework.

ASF nutritional component	Treatment in present study	Reason for boundary
Protein	AA-specific DIAAS-style replacement	Protein quantity alone does not capture indispensable amino-acid quality.
Calcium	Bioavailability-adjusted plant replacement	Crude mineral mass is not equivalent to absorbed mineral supply.
Iron	Bioavailability-adjusted plant replacement	Non-haem iron absorption varies with dietary inhibitors and enhancers.
Zinc	Bioavailability-adjusted plant replacement	Phytate and food matrix influence absorption.
Vitamin A	RAE-based replacement	Retinol and provitamin A require a defined conversion framework.
Choline	Boundary target; incremental screening extension	Retained in the nutritional boundary, but not fully integrated into the headline land optimization.
Calories	Excluded	Not required for the study's defined replacement functional unit.
B12, vitamin D, iodine, EPA+DHA	Outside ordinary cropland optimization	Requires fortified/external or specialized sources; not represented as crop-land equivalents.

VI. PROTEIN QUALITY AND DIVERSIFICATION CONSTRAINTS

A plant replacement basket can contain large amounts of crude protein while failing to reproduce the amino-acid distribution of the ASF baseline. The study therefore computes digestible indispensable amino-acid supply by crop and identifies the limiting amino acid after applying amino-acid-specific true-ileal digestibility. Diagnostic protein-only scenarios produced screening DIAAS-style values of approximately 84.0% for an equal mix, 88.6% for a soy-led mix, 86.5% for a balanced mix, 85.2% for a high-quality mix and 93.2% for a diversified mix. These values are diagnostic and should not be interpreted as final dietary adequacy.

The model also imposes diversification constraints because a mathematically efficient nutrient solution can become agriculturally unrealistic if one crop supplies nearly all of a nutrient. The locked design requires at least ten crops to contribute to protein replacement, at least five crops to contribute to each major non-protein nutrient target, and no crop to provide more than 20% of a nutrient's modeled supply share. Shared crops can contribute to several nutrients; nutrient land requirements are therefore not added independently.

The diversified optimizer in earlier workbook versions did not enforce all of these constraints simultaneously. Consequently, its lower land outputs are not used as the headline final result. This is a deliberate publication-quality decision: a numerically attractive optimization is not reported as a valid constrained solution unless all locked constraints have been demonstrated to hold.

VII. PRIMARY PRODUCT ALLOCATION AND FEED-CROPLAND REALLOCATION

The feed-cropland module uses a country-level cereal-plus-pulse dataset. The dataset is intentionally described as a coverage-defined analytical dataset rather than as a complete global feed-land inventory. It covers 100 high-volume countries, with 87 countries having complete cereal-plus-pulse observations, one country having cereal-only information and twelve countries lacking usable feed data under the specified extraction rule.

The resulting country-wise cereal-plus-pulse feed-associated cropland is 239.777 Mha/year. This is not subtracted mechanically from the replacement requirement as if all feed land were automatically transferable. The study treats the quantity as a potential feed-land credit within the defined PPA

system boundary. The credit is then applied within the representative productivity cases.

This approach is conceptually different from simply assigning every crop ultimately fed to animals to livestock. [18] emphasized the importance of distinguishing feed categories and the role of human-inedible feed in livestock systems. LUR work similarly emphasizes land suitability.

The present PPA module asks a narrower question: what crop area is associated with the primary feed-production driver within the defined dataset, and what part of that area can be represented as a potential cropland credit under the replacement scenario? Net additional annual crop-activity equivalents = replacement-system cropland − eligible feed-cropland credit

VIII. PRIMARY GLOBAL LAND BASIS

The locked primary global working basis is 659.366 Mha/year. It combines the published India PPA anchor with a harmonized rest-of-world residual. India is not extrapolated to the rest of the world. The Indian component remains an India-specific result, while the rest-of-world component is explicitly described as a harmonized residual rather than as an independently solved regional land-intensity model.

Table 3. Primary global land-balance basis and interpretation.

Component	Value	Interpretation
Primary harmonized global basis	659.366 Mha/year	Locked working basis for downstream calculations.
India anchor	186.788 Mha/year	Published India PPA result retained as an India-specific anchor.
ROW harmonized component	472.578 Mha/year	Residual harmonized component; not an independent ROW optimization.
Country feed-associated cropland	239.777 Mha/year	Coverage-defined cereal+pulse dataset; potential credit subject to PPA rules.
Post-harvest-loss sensitivity basis	760.514 Mha/year	659.366/ (1−0.133); system-level sensitivity only.

Importantly, 659.366 Mha/year is a harmonized global working basis constructed from an India-specific PPA anchor plus a rest-of-world residual; it is not the output of a spatially explicit global optimization.

This is a methodological hierarchy decision. Earlier diagnostic calculations produced alternative global values, but the final publication framework adopts 659.366 Mha/year as the single downstream primary basis. The purpose of this hierarchy is reproducibility: once a primary basis is selected, water, fertilizer, labour and GHG modules should not silently switch to another land estimate.

The primary basis should therefore be read as a working annual crop-activity requirement under the study's defined nutrient-equivalence framework. It is not a prediction of how much land would actually be converted, acquired or planted under a future policy.

IX. YIELD AND PRODUCTIVITY METHODOLOGY

The land requirement for each crop is obtained by dividing required harvest production by the corresponding yield. The model preserves crop-specific yields rather than imposing one average yield on the entire basket. This follows the production sequence established in the India study: usable nutritional output is converted to required harvest, then divided by crop-specific yield to obtain annual crop area [22].

$A_i = P_i / Y_i$

The study uses representative productivity cases informed by the logic of GAEZ yield-gap classes. FAO/IIASA GAEZ v5 reports actual-to-potential yield achievement and production gaps at high spatial resolution. The present study uses 90%, 70% and 50% representative productivity cases as scenario anchors, rather than claiming that these percentages are global frequency distributions.

This is a sensitivity framework, not a claim that all new cropland would experience the same yield penalty. It is intended to expose how quickly the land requirement grows when replacement production is moved away from an unconstrained high-productivity case toward more constrained agricultural conditions. The use of representative cases also avoids false precision from treating a heterogeneous global land base as homogeneous.

X. POST-HARVEST LOSS SENSITIVITY

A 13.3% post-harvest-loss sensitivity is propagated backward from usable nutritional output. The corresponding harvest requirement is:

$Q_{harvest} = Q_{usable} / (1 - L)$

Applying $L = 0.133$ to the 659.366 Mha primary basis produces 760.514 Mha/year as a system-level sensitivity basis. This is deliberately not described as a crop-specific measured loss rate, nor as a claim that all losses occur in the field or that all lost material is nutritionally equivalent to usable food. It is a transparent system-level sensitivity that shows the effect of requiring additional production to compensate for post-harvest losses.

The distinction matters because post-harvest loss can include storage, handling, processing and distribution losses, while field losses, seed requirements, by-product flows and residues have different system boundaries. The model therefore keeps the 13.3% sensitivity separate from seed-loss and residue modules.

XI. GAEZ-INFORMED PRODUCTIVITY SCENARIOS

A. Interpretation of the 90/70/50% Cases

The 90%, 70% and 50% cases are representative productivity scenarios informed by the concept of attainable yield and yield gaps. They are not probability distributions and should not be interpreted as saying that 90%, 70% or 50% of the world's land actually operates at those exact levels.

Their purpose is to test how sensitive the land balance is to productivity degradation or yield constraints. The range is therefore a scenario envelope, not a forecast.

B. Why Productivity and Feed Credit Must Be Coupled

A common modelling error would be to reduce replacement yields while leaving the feed-land credit unchanged. That would overstate the amount of feed land that can be reallocated into high-productivity crop production.

The present framework couples both sides. As productivity falls, replacement area rises and the usable feed credit falls. This produces a more internally consistent land balance.

The final three representative productivity cases generate a wide land range. Under the 90% case, replacement cropland is 845.016 Mha/year and the productivity-adjusted potential feed-land credit is 215.800 Mha/year, leaving 629.216 Mha/year of net additional annual crop-activity equivalents. Under 70%, replacement cropland is 1,086.449 Mha/year, the potential feed-land credit is 167.844 Mha/year, and the net additional annual crop-activity equivalent is 918.605 Mha/year. Under 50%, replacement cropland is 1,521.029 Mha/year, the potential feed-land credit is 119.889 Mha/year, and the net additional annual crop-activity equivalent is 1,401.140 Mha/year.

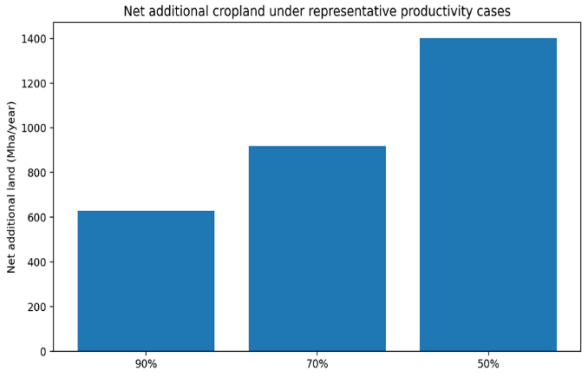


Figure 1. Net additional annual crop-activity equivalents after the productivity-adjusted potential feed-cropland reallocation credit. These are scenario outputs, not predictions of actual land conversion.

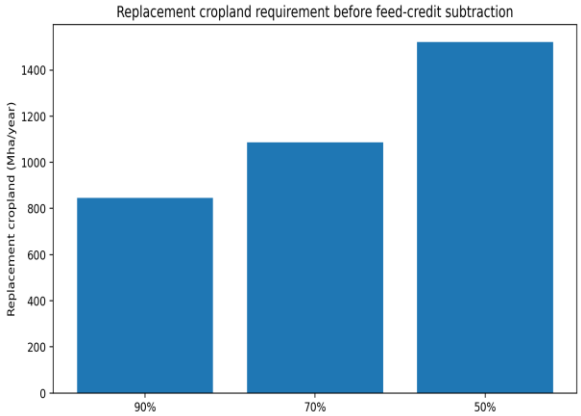


Figure 2. Gross replacement-system cropland requirement before the potential feed-cropland reallocation credit.

Table 4. Productivity-sensitive annual crop-activity requirements and potential feed-cropland credit.

Productivity case	Replacement cropland (Mha/y)	Feed credit (Mha/y)	Net additional annual crop-activity equivalents (Mha/y)	Share of 1,571 Mha global cropland
90%	845.016	215.800	629.216	40.1%
70%	1,086.449	167.844	918.605	58.5%
50%	1,521.029	119.889	1,401.140	89.2%

XII. GLOBAL CROPLAND CONTEXT

FAO's recent land assessments place global cropland at approximately 1.57 billion hectares. The present study uses 1,571 Mha as the comparison denominator. The net additional annual crop-activity requirements are therefore equivalent to approximately 40%, 59% and 89% of the 2023 global cropland area in the 90%, 70% and 50% cases, respectively; this is a scale comparison between annual crop activity and physical cropland area, not a claim that the same physical hectares must be newly converted.

These ratios should not be interpreted as saying that equivalent quantities of land would necessarily be newly cleared. The model is an area-balance exercise. Actual implementation could involve yield improvements, multiple cropping, relocation of production, dietary substitution within the plant basket, trade, technological changes, reduction of losses, use of degraded land, changes in crop composition, or a mixed system rather than a complete replacement.

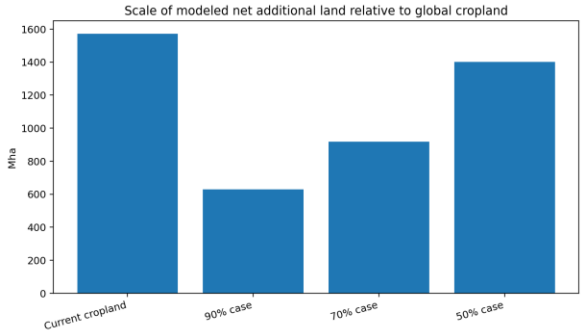


Figure 3. Scale comparison between current global cropland and modeled net additional annual crop-activity equivalents.

The comparison nevertheless provides a useful scale test. If a replacement model requires hundreds of millions of additional hectares, then productivity, land suitability, water, fertilizer and spatial allocation become first-order constraints rather than secondary details. FAO (2025a, 2025b) land and water assessments emphasize that agricultural land is already under substantial degradation pressure and that more than 1.6 billion hectares of land globally have been degraded by unsustainable management, with a large share of degradation occurring on agricultural land.

XIII. BLUE WATER, FERTILIZER AND LABOUR REQUIREMENTS

The resource modules are screening-level scaling exercises. They are not intended to replace a spatially resolved water-footprint or full LCA model. Blue-water demand is propagated from land using a screening intensity and crop-specific proxies where exact crop/form data are unavailable. The representative cases yield approximately 204.5, 298.6 and 455.4 BCM/year under the 90%, 70% and 50% productivity cases.

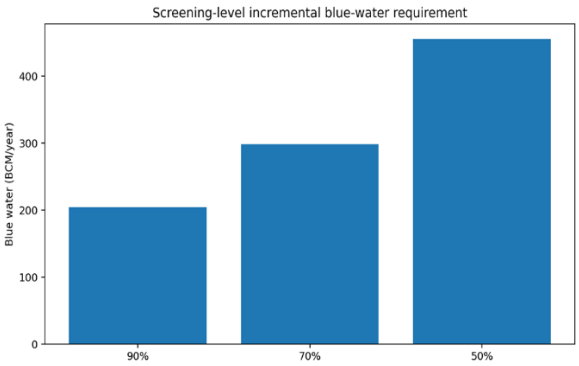


Figure 4. Screening-level incremental blue-water requirement associated with the representative productivity cases.

Fertilizer requirements are similarly scaled using global-average intensity factors. The refined screening outputs for nitrogen are approximately 78.9, 115.2 and 175.7 Mt N/year across the three cases. These are nutrient quantities, not tonnes of urea, DAP or MOP products. Organic nutrient recycling, biological nitrogen fixation and digestate credits are deliberately not netted into the direct inorganic-fertilizer

requirement; they are handled in separate recycling modules.

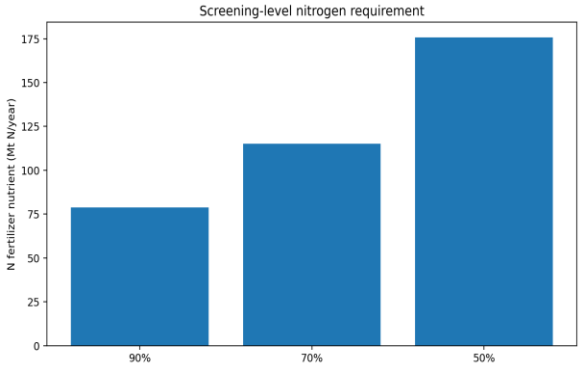


Figure 5. Screening-level nitrogen requirement. This is an incremental resource requirement under the model boundary, not a global fertilizer demand forecast.

Labour is estimated using screening intensities of approximately 81.41 labour-days per hectare for field-crop activity. The resulting annual labour demand is approximately 51,219, 74,775 and 114,053 million labour-days for the 90%, 70% and 50% cases. These figures represent annual resource demand, not jobs or headcount, because one worker can supply labour-days across seasons and locations.

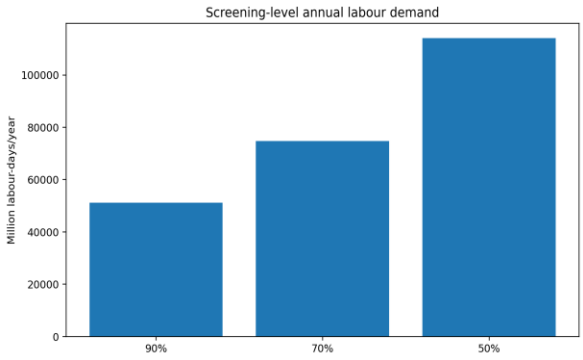


Figure 6. Screening-level annual labour demand. The values represent labour-days, not employment headcount.

XIV. GREENHOUSE-GAS ACCOUNTING BOUNDARY

GHG accounting is separated into direct replacement-system emissions, fertilizer transport, land-use-change carbon debt, livestock phaseout emissions, hypothetical animal-disposal emissions, crop-residue/crop-by-product landfill emissions, and manure/biogas opportunity-cost modules. This prevents avoided livestock emissions, one-time land carbon debt, waste-management emissions and operational crop emissions from being combined as though they had identical temporal profiles.

The agriculture-to-agriculture comparison uses an existing crop-plus-livestock benchmark of approximately 8.1 Gt CO2e/year, decomposed here into approximately 3.8 Gt CO2e/year from the existing plant/crop system and 4.3 Gt CO2e/year from livestock. Because this study replaces only the nutritional contribution of animal-source foods, the existing 3.8 Gt CO2e/year plant-system burden is retained in the replacement scenario. The 4.3 Gt CO2e/year livestock component is treated as the phaseout burden that is progressively removed; it is not carried into the replacement-system total.

The study uses a deliberately defined 10-year amortization convention for land-use-change (LUC) carbon debt. For the grassland-to-cropland pathway, the 5.9 t CO2e/ha/year screening factor is taken from [8], which applies an IPCC Tier 1 grassland-to-cropland factor of 118 t CO2e/ha over a 20-year transition and linearly annualizes it to 5.9 t CO2e/ha/year. For the forest-to-cropland pathway, the 7.3 t CO2e/ha/year factor is from [14]; that source annualizes carbon-stock changes using a 100-year averaging convention. The present study does not adopt either source's amortization horizon as its own accounting horizon. Instead, it deliberately applies a 10-year study accounting convention, yielding 59 and 73 t CO2e/ha as the corresponding ten-year accounting equivalents. The reported annual GHG totals therefore represent LUC carbon debt amortized over 10 years within this study boundary; they do not represent a 100-year amortization, nor do they claim that carbon is physically emitted at a constant rate over ten years. 10-year LUC cumulative equivalent = area × annualized LUC factor × 10; annualized LUC burden = 10-year cumulative equivalent / 10

For the 90% case, the grassland conversion sensitivity is approximately 0.880 Gt CO2e/year when the ten-year cumulative carbon debt is annualized, corresponding to approximately 8.804 Gt CO2e over ten years. The forest high case is approximately 1.089 Gt CO2e/year annualized, or 10.893 Gt CO2e over ten years. These values are accounting sensitivities, not direct forecasts of actual land conversion.

A. Whole-System Replacement Accounting

The central accounting correction is that the replacement calculation is incremental. It estimates the additional plant production needed to replace the nutritional contribution currently supplied by animal-source foods; it does not remove the plant foods and crop production that already feed the population.

Accordingly, the existing 3.8 Gt CO2e/year plant-system burden remains in the replacement-system total. The existing 4.3 Gt CO2e/year livestock burden is the component that is phased out and therefore is not retained in the replacement total.

The corrected replacement-system total is therefore: 3.8 Gt CO2e/year existing plant system + incremental replacement-production emissions + land-use-change burden + animal-disposal sensitivity + upstream LPG replacement burden. A separate crop-waste/by-product landfill sensitivity is then added because some biomass previously consumed by livestock may require an alternative end-of-life pathway.

The incremental replacement-production term includes field N2O, fertilizer manufacture, agricultural machinery, irrigation electricity associated with water use, and fertilizer transport. Water itself is not assigned a direct GHG coefficient; its energy requirement is represented through irrigation electricity.

The LUC burden is explicitly amortized over 10 years using the study boundary in which only land beyond the 480 Mha degraded-land reference pool receives the LUC burden. Thus, the LUC terms are not applied mechanically to the entire net additional annual crop-activity equivalents requirement. The resulting Gt CO2e/year values are 10-year-amortized accounting burdens, not 100-year annualized emissions and not a claim about the physical timing of carbon release.

For the 90% productivity case, the resulting whole-system total is approximately 5.588 Gt CO2e/year under the grassland-LUC pathway and 5.797 Gt CO2e/year under the forest-LUC pathway.

At 70% productivity, the corresponding totals are approximately 7.602 and 8.216 Gt CO2e/year, respectively, placing the grassland case below but the forest case slightly above the 8.1 Gt CO2e/year existing-system benchmark.

At 50% productivity, totals rise to approximately 10.960 Gt CO2e/year for the grassland pathway and 12.250 Gt CO2e/year for the forest pathway, exceeding the existing-system benchmark in both cases.

The 8.1 Gt CO2e/year benchmark is therefore a whole-system comparator, whereas the 0.667, 0.974 and 1.485 Gt CO2e/year production terms are incremental replacement-production burdens. These quantities should never be compared across mismatched boundaries. The 0.235 Gt CO2e/year animal-disposal value remains a hypothetical transition sensitivity, not a recurring livestock emission. Similarly, the approximately 0.005284 Gt CO2e/year LPG term represents upstream LPG production/import/transport associated with replacing the current 40 bcm/year manure-biogas benchmark and excludes LPG combustion unless separately specified.

The 21.5 Gt CO2e cumulative avoided-emissions value from a linear ten-year livestock phaseout remains a separate transition metric and is not subtracted from the replacement-system annual total.

This provides a conservative whole-system comparator: the existing 3.8 Gt CO2e/year crop-system baseline is retained, while the 4.3 Gt CO2e/year livestock component is removed and incremental replacement-production emissions are added. The accounting does not separately credit avoided emissions from reduced feed-crop production because those emissions are not spatially resolved within the present model.

Table 5. Corrected whole-system GHG accounting. All values are Gt CO2e/year; the 3.8 Gt crop-system baseline is retained in the replacement scenario.

Productivity	Existing plant (Gt/y)	Incremental production (Gt/y)	Grassland LUC (10-y amortized Gt CO2e/y)	Forest LUC (10-y amortized Gt CO2e/y)	Disposal (Gt/y)	LPG (Gt/y)	Total – grassland (Gt/y)	Total – forest (Gt/y)
90%	3.800	0.667	0.880	1.089	0.235	0.005	5.588	5.797
70%	3.800	0.974	2.588	3.202	0.235	0.005	7.602	8.216
50%	3.800	1.485	5.435	6.724	0.235	0.005	10.960	12.250
Existing system	3.800	—	—	—	—	—	8.100	8.100

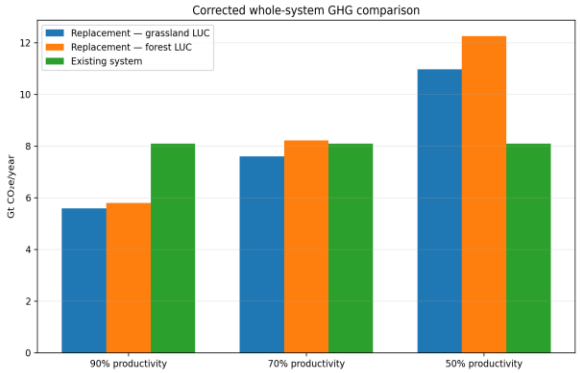


Figure 7. Whole-system GHG comparison after retaining the existing 3.8 Gt CO2e/year plant-system baseline.

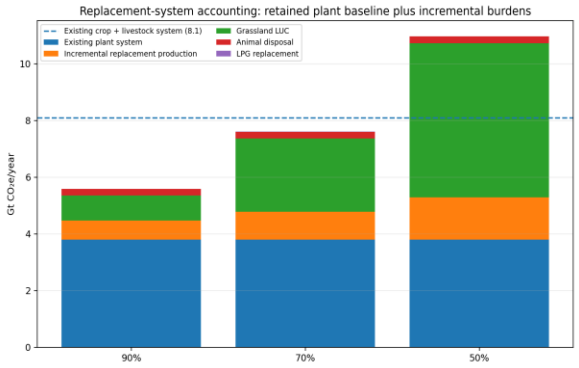


Figure 8. Component accounting for the grassland-LUC pathway; the dashed line marks the 8.1 Gt CO2e/year existing crop-plus-livestock benchmark.

XV. TEN-YEAR ANIMAL-AGRICULTURE PHASEOUT

A separate sensitivity examines a linear ten-year phaseout of the 4.3 Gt CO2e/year livestock baseline. Under a linear decline from 100% in year one to zero in year ten, cumulative emissions during the transition equal the area of a triangle: 4.3 × 10/2 = 21.5 Gt CO2e. Against a counterfactual in which the baseline continues unchanged for ten years, cumulative avoided emissions are also 21.5 Gt CO2e.

Cumulative transition emissions = baseline × 10/2 = 21.5 Gt CO2e

The avoided amount is not subtracted from crop-system emissions as an artificial negative emission. It is reported separately as a phaseout comparison. This distinction preserves temporal and causal integrity: avoided future emissions are not the same thing as removal of carbon dioxide from the atmosphere.

XVI. ANIMAL DISPOSAL SENSITIVITY AND MANURE/BIOGAS MODULES

The workbook includes a hypothetical unmanaged animal-disposal/decomposition sensitivity of approximately 235 Mt CO2e/year, amortized over ten years to represent a one-time disposal burden. This is explicitly a screening scenario, not a recurring livestock emission and not an empirical estimate of what a managed phaseout would necessarily produce. Actual carcass management could involve rendering, composting, controlled burial or other pathways with different emission profiles.

Manure and biogas are treated as opportunity-cost and circularity modules. The author's 2025 global cattle-and-buffalo dung assessment estimated approximately 6.63 billion tonnes of dung and 198.9 billion m³ of theoretical biogas under a 50% methane-content baseline [21]. The present study does not simply count this theoretical energy potential as a negative emission against the crop system. Instead, it recognizes that manure can provide energy and nutrients within integrated systems and that allocating the same biomass simultaneously to multiple benefits requires an explicit allocation rule.

This boundary is important for circular agriculture. A crop-livestock system can recycle residues and manure without necessarily satisfying every criterion of a circular-economy business model. Agricultural circularity is a system property involving material and nutrient cycling; circular economy is a broader economic framework involving value chains, markets, waste reduction and resource recirculation.

They overlap but should not be treated as synonyms. 16A. Crop-Waste and Crop-By-Product Landfill Sensitivity Animal-agriculture phaseout creates a second waste-boundary issue that is distinct from animal carcass disposal. The replacement crop system generates residues and processing co-products, while the existing livestock system currently consumes part of the global crop-residue and crop-by-product stream as feed. If animal agriculture is removed, biomass that is no longer used as feed may remain on the field, be incorporated into soil, be burned, be used for bioenergy or biogas, enter other industrial uses, or be disposed of as solid waste. Therefore, the study does not assume automatically that all displaced feed biomass becomes landfill waste; landfill disposal is treated as a sensitivity.

The narrow feed-only reference boundary identifies approximately 598 Mt dry matter/year of crop residues formerly used as livestock feed, 311 Mt/year of cereal-processing by-products, and 18.3 Mt/year of sugar-processing by-products. Oilseed meals are excluded because the replacement nutrition system can use these co-products, avoiding double counting. These quantities are reference feed-associated flows, not observed global landfill flows.

For landfill screening, the model applies category-specific degradable-organic-carbon parameters, a methane correction factor of 0.6, 50% methane in landfill gas, zero oxidation in the conservative gross-emission case, and AR6 methane GWP100 of 27.2 t CO2e/t CH4. CH4 is calculated as waste mass × DOC × DOCf × MCF × methane fraction × 16/12 × landfill diversion fraction. The result is converted to CO2e. This is a potential/steady-state screening estimate; a full first-order-decay model is required for a time-resolved ten-year phaseout.

Table 6. Narrow feed-only crop-waste/by-product landfill sensitivity. The 50% case is the recommended central illustrative sensitivity; it is not an observed global landfill fraction.

Landfill diversion	Biomass diverted*	Additional landfill GHG	90% grassland-LUC total	70% grassland-LUC total
0%	0	0	5.588	7.602
25%	231.825 Mt DM/y	0.248 Gt CO2e/y	5.836	7.850
50%	463.650 Mt DM/y	0.496 Gt CO2e/y	6.084	8.098
100%	927.300 Mt DM/y	0.993 Gt CO2e/y	6.581	8.595

Under the 50% central landfill sensitivity, the additional burden is approximately 0.496 Gt CO2e/year. The corresponding grassland-LUC replacement-system totals are approximately 6.084, 8.098 and 11.456 Gt CO2e/year for the 90%, 70% and 50% productivity cases, respectively. Under the forest-LUC pathway the corresponding totals are approximately 6.293, 8.712 and 13.243 Gt CO2e/year. Thus, when 50% of the displaced feed-associated biomass is assumed to enter landfill, the 70% productivity case is approximately at or above the existing 8.1 Gt CO2e/year whole-system benchmark depending on the LUC pathway.

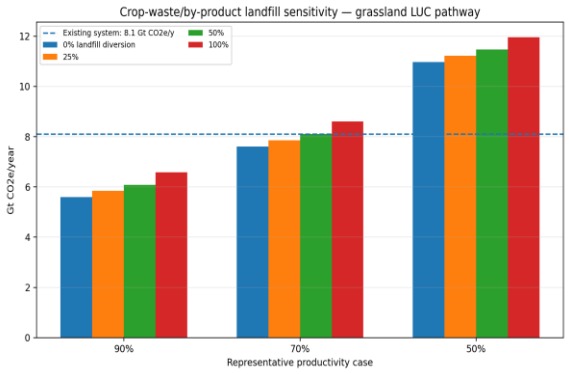


Figure 9. Crop-waste/by-product landfill GHG sensitivity under the narrow feed-only boundary. The dashed line is the existing 8.1 Gt CO2e/year crop-plus-livestock benchmark.

This landfill module is deliberately separate from crop-residue biogas and organic-fertilizer pathways. The same residue fraction cannot simultaneously receive a full landfill burden and a full biogas or nutrient-recycling credit. Crop residues retained on fields are not assigned landfill methane. The sensitivity quantifies the climate consequence of a defined adverse end-of-life pathway if feed-associated biomass becomes waste after animal-agriculture phaseout.

Source basis: [24] for global feed-flow shares; [26] for cereal-residue animal-use context; IPCC (2006, 2019) for landfill organic-carbon parameters. The landfill result is a screening sensitivity and should not be interpreted as a measured global waste-sector emission.

XVII. COMPARISON WITH POORE AND NEMECEK

[20] and the present study should be compared as complementary analyses rather than as mutually exclusive estimates. Their work is a global food-footprint LCA and scenario analysis. The present study is a nutritional-equivalence agricultural land-balance model. The former asks how environmental footprints change when the food system shifts toward different dietary patterns; the latter asks how much

crop activity is required to reproduce a defined existing ASF nutritional contribution under a constrained plant-production system.

Table 7. Comparison of [20] with the present nutritional-replacement framework.

Dimension	Poore & Nemecek (2018)	Present study
Primary question	Environmental footprint of foods and modeled dietary shift	Cropland needed for defined nutritional replacement of existing ASF supply
Functional unit	Food products and dietary scenario	Nutritional-equivalence replacement; annual crop activity
Land scope	Agricultural land including pasture and feed	Crop production and explicit feed-cropland credit
Nutrition	Food quantities and dietary scenario	ASF-derived nutrient targets with DIAAS/bioavailability framework
Co-products	LCA allocation framework	Primary Product Allocation for defined feed-purpose module
Yield treatment	Observed production systems and scenario modelling	Crop-specific yield basis plus 90/70/50% representative productivity cases
Headline land interpretation	Large reduction in total agricultural land under plant-only scenario	Large additional crop-area requirement under constrained complete replacement
Interpretation	Scenario environmental footprint	Agricultural production feasibility/area-balance test

The difference is therefore not evidence that one method is false. It is evidence that land accounting is functional-unit dependent.

A model can find that total agricultural land decreases because pasture disappears while simultaneously finding that direct cropland demand for replacement food increases. Both statements can be true if they refer to different land pools and different functional units.

XVIII. COMPARISON WITH LAND-USE-RATIO STUDIES

LUR studies explicitly recognize that land quality matters. [29] defined LUR as the human-digestible protein that could be produced from food crops on the land used to produce feed for one kilogram of ASF divided by the human-digestible protein in that ASF. Their illustrative results included an LUR of 2.08 for laying hens, 2.10 for dairy cows on sandy soils and 0.67 for dairy cows on peat soils. The result changes because land suitability changes.

[27] extended the LUR framework using geospatial crop suitability and yield information for beef systems in the northeastern United States. Their systems had LUR values above one, illustrating that feed-land opportunity cost can be substantial when forage land is suitable for cropping. The authors also emphasized that land-use interpretation depends on whether forage land is marginal or productive.

The present study incorporates the same conceptual insight land productivity and suitability matter but does not calculate a global LUR for every livestock system. Instead, it uses a potential feed-cropland reallocation credit within a global nutritional replacement model and then tests how the replacement system performs under representative productivity constraints. LUR and this study are therefore complementary rather than interchangeable.

XIX. PLANT-BASED DIETARY LITERATURE AND CROPLAND HETEROGENEITY

The broader plant-based dietary literature generally finds reductions in GHG emissions and total land use relative to conventional dietary patterns, but the magnitude and even the direction of cropland-only changes can vary with food composition, geography and the functional unit. [1], in a scoping review of 65 eligible studies, found broad agreement that plant-based patterns tend to reduce GHG emissions, land use and biodiversity loss, while water and energy outcomes depend more strongly on the foods selected. This heterogeneity is important because a vegan or whole-plant dietary label does not uniquely specify a crop basket. A dietary pattern rich in grains, legumes,

nuts, fruits, vegetables and oils can have a different cropland footprint from a highly processed pattern or a diet emphasizing low-yield nutrient-dense crops. Similarly, replacing animal foods with plant foods on a nutrient-mass basis can differ substantially from replacement using digestibility-adjusted protein and nutrient-specific bioavailability.

The present study therefore avoids the statement that a whole-plant diet universally requires more cropland than the current global food system. Its narrower finding is that a complete nutritional replacement of existing ASF supply, under the study's constrained crop and productivity framework, can require a very large additional crop area. This is consistent with the broader literature's recognition that land outcomes depend on the dietary and agricultural specification.

XX. INTEGRATED FARMING SYSTEMS AND THE 700-STUDY MCLS META-ANALYSIS

Integrated farming systems (IFS) provide a different systems perspective from both product LCA and crop-only replacement models. ICAR reviews describe IFS as combinations of crops, livestock, fish, horticulture and other enterprises in which outputs or wastes from one component can become inputs to another. [15] emphasize resource recycling, livelihood diversification and the ability of multi-component systems to supply multiple food and livelihood functions. [25] similarly describe potential gains in system productivity, resource-use efficiency, employment and climate resilience.

The recent global meta-analysis by [17] synthesizes 700 studies from 270 publications. Across the evidence base, mixed crop-livestock systems were associated on average with lower production costs, lower income variability, higher physical productivity and net income, lower GHG emissions, lower non-renewable energy use, lower nitrogen surplus and pesticide use, and higher biodiversity and soil organic carbon. However, the meta-analysis also found that nearly 95% of the studies showing both economic and environmental performance were experiments or simulations; among real-farm studies, only 12% supported double performance. This qualification is crucial when translating experimental potential into global farm-scale expectations.

The implication for the present study is not that integrated farming invalidates a crop-only land balance. Rather, it shows why a crop-only replacement scenario should not be interpreted as the only feasible food-system pathway. Integrated systems can generate multiple outputs from the same physical land and can recycle nutrients and residues. Conversely, integration is not a guarantee of superior performance in every location. The correct comparison is system-specific and should preserve the boundaries of each production system.

Table 8. Evidence base for integrated farming systems and its use in the present framework.

Evidence source	What it contributes	How it is used here
Kumar et al. (2018), ICAR	Indian IFS evidence and resource-recycling framework	Context for multifunctional agricultural systems.
Singh et al. (2020), ICAR	Productivity, resilience and livelihood perspective	Context for system productivity beyond crop-only metrics.
Minviel & Veysset (2026)	Global 700-study MCLS synthesis	Evidence that integration can improve multiple outcomes, with strong real-farm caveats.
IPCC AR6	Integrated systems can increase food per land unit and buffer climate risk in some contexts	Global systems-context evidence; scalability remains uncertain.
Present study	Nutritional-equivalence crop-land balance	Quantifies a defined replacement counterfactual rather than an integrated-system optimum.

XXI. KEY RESULTS: SYNTHESIS

The central result is the wide productivity-sensitive range of net additional annual crop-activity equivalents: 629.216 Mha/year at the 90% representative productivity case, 918.605 Mha/year at 70%, and 1,401.140 Mha/year at 50%. The lower case alone is approximately 40% of current global cropland. The 50% case approaches 90% of the current cropland denominator.

Three mechanisms drive the range. First, lower crop productivity increases the amount of land required to

produce the same nutrient-equivalent output. Second, the potential feed-cropland reallocation credit declines in the lower-productivity cases because the modeled credit is itself productivity-dependent. Third, the replacement system must maintain nutritional diversity and cannot simply allocate all nutrients to the single crop that minimizes one land metric.

The 13.3% post-harvest-loss sensitivity raises the primary basis from 659.366 to 760.514 Mha/year before productivity adjustments. This demonstrates that loss reduction is not merely a supply-chain issue; in a strict nutritional-equivalence land balance, every percentage of usable-output loss propagates backward into additional production requirements.

Resource demand rises in parallel with land. Blue-water screening increases from approximately 204.5 to 455.4 BCM/year across the three cases, nitrogen from approximately 78.9 to 175.7 Mt N/year, and annual labour demand from approximately 51.2 to 114.1 billion labour-days. These figures reinforce the conclusion that land is only one dimension of replacement feasibility.

XXII. SENSITIVITY AND ROBUSTNESS INTERPRETATION

The scenario range should be treated as a structured sensitivity envelope rather than a probability interval. The 90%, 70% and 50% cases do not represent probabilities that global agriculture will achieve those exact productivity levels. They represent progressively more constrained production environments, motivated by the existence of yield gaps and spatial heterogeneity documented in GAEZ.

The model is also sensitive to the crop portfolio. Earlier India work demonstrated that different six-crop portfolios produce material differences in annual crop activity and resource requirements even when the nutritional target is held constant [22]. This global study therefore avoids claiming that one crop mix is the unique optimum.

A further robustness principle is that the study keeps derived values visibly separate from source observations. The 1,571 Mha global cropland denominator is a source statistic; 629.216 Mha is a model output; 40.1% is a derived comparison; and 59 or 73 t CO2e/ha over ten years is a cumulative accounting sensitivity derived from an annualized source factor. Maintaining these categories is necessary to prevent derived outputs from being mistaken for reported empirical measurements.

XXIII. IMPLICATIONS FOR FOOD-SYSTEM MODELLING

First, nutritional equivalence should be defined before land comparisons are made. Replacing 1 kg of protein with 1 kg of plant protein is not necessarily equivalent to replacing the digestible indispensable amino-acid contribution of ASF. Likewise, replacing crude calcium or iron mass is not equivalent to replacing bioavailable mineral supply.

Second, crop-purpose allocation should be explicit. Feed land cannot be inferred solely from the ultimate use of all crop co-products. Conversely, a crop grown primarily for feed should not disappear from the feed-land balance simply because some co-products enter human markets. PPA provides a transparent way to state which production driver is being counted.

Third, land-quality information should be integrated. LUR studies demonstrate that the same quantity of pasture can have very different opportunity costs depending on whether it is suitable for direct food cropping. The present GAEZ sensitivity extends that principle to the replacement side: replacement production also depends on attainable yield and yield gaps.

Fourth, integrated farming should be evaluated as a distinct system rather than inserted into a crop-only model as an unquantified benefit. Nutrient recycling, manure biogas, livestock by-product utilization and multifunctional land use can change system balances, but each credit requires a defined allocation and should not be double counted.

XXIV. LIMITATIONS

A. Priority Limitations for Future Revision

The most important limitation is the harmonized nature of the 659.366 Mha basis. A future version should solve country-level crop mixtures simultaneously rather than combining an India anchor with a harmonized ROW component.

The second major limitation is the feed dataset boundary. The 239.777 Mha estimate should be expanded to a complete global feed-land inventory with explicit trade, co-product and pasture distinctions.

The third is nutrient evidence. Better crop-form-specific human digestibility data could materially alter the optimized crop mixture and therefore the land requirement.

B. What Would Most Improve Precision

Spatial resolution would provide the largest improvement. A future model should connect each crop to agroecological-zone yields, irrigation requirement, fertilizer response, soil nutrient balance and land suitability. The nutritional optimizer could then choose among locations as well as crops.

This would transform the current scenario framework into a spatial optimization model.

The first major limitation is that 659.366 Mha/year is a harmonized working basis, not a fully re-solved global optimization. India is anchored to a published PPA result, while the rest-of-world component is a harmonized residual. This is transparent but means that the global figure should not be presented as a mathematically unique global optimum.

Second, the country feed-land dataset is coverage-defined rather than a complete global feed-cropland inventory. Missing observations are retained as NA and not silently filled. Consequently, the 239.777 Mha figure should be called the modeled feed-associated cropland of the defined country dataset.

Third, protein-quality and bioavailability factors are evidence-mapped screening parameters. Direct human true-ileal data are used where available; category midpoint proxies are used where evidence is incomplete. This is preferable to inventing crop-specific empirical values, but it limits the precision of the final nutrient basket.

Fourth, the resource modules are screening-level. Blue water is not a basin-resolved water scarcity model; fertilizer intensity is not a crop-by-country nutrient-management optimization; labour is not an employment forecast; and GHG results are not a complete cradle-to-grave LCA.

Fifth, the study does not model trade, market prices, food access, infrastructure, policy constraints, land tenure, biodiversity opportunity costs, ecosystem services of pasture, or regional crop suitability at full spatial resolution. These are important areas for subsequent research.

Finally, the study is a counterfactual agricultural systems model. It should not be interpreted as a forecast that governments or consumers will adopt a complete plant-only transition, nor as evidence that any particular dietary pattern is universally optimal.

XXV. CONCLUSIONS

A. Overall Scientific Interpretation

The central finding is not simply a single land number. It is that global agricultural land requirements depend on the definition of nutritional equivalence and the productivity conditions under which replacement is attempted.

The study provides a transparent framework in which nutritional targets, crop yields, feed-land reallocation and resource requirements are linked. This creates a basis for comparison with LCA and LUR studies without claiming that any one framework is universally sufficient.

B. Research Contribution

The methodological contribution is the integration of nutritional equivalence, AA-specific protein quality, nutrient-specific bioavailability, PPA, feed-land reallocation and productivity sensitivity into a single agricultural land-balance framework. The approach is deliberately conservative about missing evidence and explicit about what remains screening-level.

This study demonstrates that global land requirements for ASF replacement are highly sensitive to the analytical question and system boundary. A nutritional-equivalence model that replaces the existing ASF nutritional contribution with a diversified plant-crop system produces a primary harmonized working basis of 659.366 Mha/year and, under representative productivity constraints, net additional annual crop-activity equivalents of approximately 629.216 to 1,401.140 Mha/year after the productivity-adjusted potential feed-land credit.

The result should be interpreted alongside not against— [20], LUR studies, plant-based dietary literature and integrated-farming evidence. LCA, LUR, PPA and nutritional-equivalence approaches measure different relationships between land, food and production. The most scientifically defensible

conclusion is therefore methodological: land-use results are conditional on the functional unit, allocation rule, nutritional target, productivity basis and system boundary.

The analysis also shows that land is inseparable from water, fertilizer and labour. A large crop-area requirement propagates into substantial resource demand, especially when productivity constraints become more severe. Conversely, improvements in yield, post-harvest loss reduction, nutrient recycling, crop diversification, multiple cropping and appropriate land allocation can materially change the result.

Integrated farming evidence further indicates that future food-system analysis should not be limited to crop-only or animal-only specialization. Mixed systems can create resource-recycling and multifunctional benefits, although recent meta-analysis shows that strong real-farm evidence is less conclusive than experimental and simulation evidence. The appropriate next step is therefore not a universal ranking of plant-only versus animal-containing agriculture, but spatially explicit, nutritionally equivalent, multifunctional food-system modelling.

In summary, the principal contribution of this work is a transparent bridge between nutritional equivalence and agricultural land accounting. It makes explicit what is often implicit: replacing a food category is not the same analytical problem as reducing its environmental footprint, and the answer changes when nutrition, land quality, crop purpose, productivity and system integration are treated explicitly.

XXVI. DATA AVAILABILITY AND REPRODUCIBILITY

The analysis is based primarily on publicly available FAOSTAT, FAO/IIASA, IPCC, and published literature inputs. The master calculation workbook contains source registers, nutritional evidence, crop inputs, yield modules, feed-land extraction, resource modules, greenhouse-gas modules, land-use-change sensitivities, and audit sheets. The calculation workbook, evidence register, and derived analytical tables are available from the author upon reasonable request. A versioned public repository deposit should accompany the final published record. The current workbook is also maintained at https://agrisuku.wordpress.com/2026/10/07/global-asf-replacment-cropland-computation-masterworkbook-sukumar-radrapu/.

The reproducibility materials comprise the final calculation workbook, machine-readable country feed-land tables, crop nutrient and amino-acid matrices, the evidence register, calculation notes for the representative GAEZ-informed productivity cases, and a versioned change log. Screening proxies are explicitly identified so that they can be replaced without altering the underlying calculation structure.

AUTHOR CONTRIBUTIONS

Sukumar Radrapu conceived and designed the study, developed the analytical framework, compiled and evaluated the source data, performed the calculations, interpreted the results, and wrote and revised the manuscript.

AI USE STATEMENT

AI-assisted tools were used during manuscript development to assist with language editing, document organization, literature cross-checking, and methodological critique. All scientific calculations, source verification, methodological decisions, interpretations, and final manuscript content were reviewed and approved by the author, who retains full responsibility for the accuracy and integrity of the work.

DECLARATIONS

Funding: No external research funding is declared for the present analysis.

Conflict of interest: The author declares no competing financial interest relevant to the methodological analysis. The author's previous publications are cited where they provide methodological or empirical context; their inclusion does not constitute independent validation of the present results.

Ethics statement: The study uses aggregated secondary agricultural, food-balance, environmental and literature data and does not involve human or animal subjects.

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APPENDIX A. EQUATION COMPENDIUM

A1. Nutritional replacement production: Required crop production = nutritional replacement target / nutritional contribution per unit usable crop output.

A2. Crop area: $A_i = P_i / Y_i$, where A_i is annual crop area, P_i required production and Y_i crop yield.

A3. Total crop activity: $A_total = \Sigma A_i$.

A4. Post-harvest loss: Q_harvest = Q_usable / (1 − L).

A5. Gross-to-physical land: Physical land = GCA / cropping intensity.

A6. Net land after feed credit: A_net = A_replacement − A_feed_credit.

A7. Land-use-change carbon debt: The study amortizes the LUC carbon debt over 10 years. Ten-year cumulative accounting equivalent = area × annualized LUC factor × 10; annualized 10-year burden = ten-year cumulative equivalent / 10.

A8. Linear phaseout: Cumulative transition emissions = baseline × duration / 2.

APPENDIX B. PUBLICATION INTERPRETATION RULES

1. Do not describe the 659.366 Mha/year primary basis as a global mathematical optimum.
2. Do not describe 239.777 Mha/year as a complete global feed-cropland inventory.
3. Do not describe the 13.3% loss sensitivity as a crop-specific measured loss rate.
4. Do not describe 59 or 73 t CO2e/ha as annual emissions; they are ten-year cumulative equivalents derived from annualized source factors. The paper uses a deliberate 10-year LUC amortization convention; the reported annual LUC burden is the corresponding ten-year carbon debt divided by 10.
5. Do not subtract cumulative avoided livestock phaseout emissions from crop-system emissions as artificial negative emissions.

6. Do not count manure, biogas, residue and fertilizer credits twice across modules.
7. Do not use the earlier unconstrained diversified optimizer outputs as the final headline land requirement.
8. Do not interpret modeled land area as land acquisition, land conversion or policy prescription.
9. Use the terms 'scenario output', 'screening estimate', 'working basis' and 'system consideration' where appropriate.

APPENDIX C. PRIMARY PUBLICATION TABLE

Table 9. Synthesis of principal land and resource outputs across the productivity scenarios.

Metric	90%	70%	50%	Unit
Replacement cropland	845.016	1,086.449	1,521.029	Mha/year
Feed-land credit	215.800	167.844	119.889	Mha/year
Net additional annual crop-activity equivalents	629.216	918.605	1,401.140	Mha/year
Share of current global cropland	40.1%	58.5%	89.2%	%
Blue water screening	204.5	298.6	455.4	BCM/year
N fertilizer screening	78.9	115.2	175.7	Mt N/year
Labour screening	51,218.8	74,774.9	114,053.1	million labour-days/year

Note on figures: All headline numerical results in this article are study calculations from the locked publication framework. External literature is used for source parameters, methodological comparison and contextual interpretation. Where a screening proxy is used, it is identified as such rather than presented as a direct empirical observation.

APPENDIX D. DETAILED NUTRITIONAL-SYSTEM BOUNDARY

The nutritional boundary is intentionally narrower than a full dietary adequacy model. The starting point is the nutritional contribution represented by existing animal-source-food supply, not the amount of food that would be recommended for a healthy population. This avoids embedding an independent dietary prescription into the land calculation. The model then asks what plant production is required to reproduce that defined contribution after accounting for protein quality and nutrient-specific bioavailability.

For protein, the model follows the logic of indispensable amino-acid supply. The limiting amino acid is identified after applying amino-acid-specific true-ileal digestibility and comparing digestible indispensable amino acids with the FAO reference pattern. This is preferable to multiplying total protein by a single digestibility factor because the nutritional value of a protein mixture depends on both amino-acid composition and digestibility. The distinction is particularly important for pulses, nuts and oilseeds, where amino-acid patterns and anti-nutritional factors vary by crop and processing form.

For calcium, iron and zinc, the model does not assume that equal mineral mass implies equal nutritional delivery. Iron and zinc are affected by food matrix and phytate, while calcium absorption can vary with the composition of the overall diet. The model therefore applies nutrient-specific screening adjustments. Vitamin A is represented as retinol activity equivalents, while choline is retained as a boundary target but its crop-side replacement remains an incremental screening extension rather than a fully integrated component of the headline land optimization. Calories are excluded because the study is not designed to determine a complete energy-balanced diet.

The model deliberately keeps B12, vitamin D, iodine and EPA+DHA outside the ordinary cropland optimization. This does not imply that these nutrients are impossible to obtain in plant-inclusive systems. It means that a crop-area equation alone cannot demonstrate their complete replacement without introducing fortification, supplementation, food processing or specialized production assumptions. Keeping them outside the land equation is therefore a boundary-control decision rather than a nutritional judgement.

The resulting framework should be understood as a nutrient-replacement stress test. It asks how much agricultural production is required under a specified equivalence rule. It does not certify that the modeled

crop basket is a complete practical diet for any individual or population.

APPENDIX E. EVIDENCE-MAPPING RULES FOR PROTEIN QUALITY

The protein-quality module uses a hierarchy of evidence. Direct human true-ileal amino-acid digestibility measurements are preferred. When direct crop-and-form observations are incomplete, the model uses an explicitly identified category-range midpoint proxy.

This hierarchy avoids silently replacing missing data with optimistic or pessimistic values.

Soy provides an example of the distinction. Human true-ileal data are available for particular soy protein products, but a product-form value is not automatically identical to the digestibility of an unprocessed whole soybean. The model therefore labels soy evidence as a product-form proxy where appropriate. For chickpea and mung bean, human-adult amino-acid digestibility studies provide more direct evidence. Faba bean evidence includes direct protein-quality work. Other pulses may require category-level screening values.

The FAO reference pattern is applied after the digestible indispensable amino-acid supply is calculated. The general screening equation is:

Digestible IAA_j = Σ_i (protein share_i × IAA concentration_i × TID_i,j)

where i indexes crops and j indexes indispensable amino acids.

The DIAAS-style screening value is then the lowest ratio of digestible IAA supply to the corresponding FAO reference pattern.

The purpose of this module is not to generate a clinically definitive dietary score. It is to prevent the land model from treating all grams of crude plant protein as nutritionally interchangeable with ASF protein. That distinction is central to the study's functional unit.

The evidence-mapping rule also provides a reproducibility safeguard. Every proxy should be tagged as direct evidence, category evidence, product-form evidence, or model screening value. A future version of the model can then replace only the proxy values for which better evidence becomes available without changing the overall calculation architecture.

APPENDIX F. FEED-CROPLAND DATASET AND MISSING-DATA TREATMENT

The feed-cropland module is deliberately conservative in its treatment of missing observations. A country is included in the complete cereal-plus-pulse calculation only when the required observations are available under the specified extraction rule. Where a country has cereal data but no usable pulse observation, it is not silently assigned a pulse value. Where neither is available, the observation is retained as missing.

This approach produces a dataset with 87 countries having complete cereal-plus-pulse information, one cereal-only observation and twelve countries without usable feed data among the defined high-volume country set. The resulting 239.777 Mha/year is therefore a dataset-defined estimate. It should not be presented as a universal global feed-cropland number.

The purpose of the feed module is not to reproduce every kilogram of global feed demand. Its purpose is to establish a transparent, auditable pool of crop area that can potentially receive a land credit when the primary production purpose is livestock feed and when the land can be represented within the replacement scenario.

The PPA rule is particularly important for co-products. If a crop is cultivated primarily for a human food or industrial market and livestock receive a by-product, the whole crop area is not automatically transferred into the animal-feed category. Conversely, a crop specifically cultivated for feed should remain in the feed category even if some material is subsequently diverted. This is why production purpose and downstream use must be documented separately.

The feed credit is also productivity-dependent. At 90% representative productivity the modeled credit is 215.800 Mha; at 70% it is 167.844 Mha; and at 50% it is 119.889 Mha. The declining credit prevents the model from treating low-productivity replacement land as though every hectare of feed land could be converted into an equally productive food-cropping hectare.

APPENDIX G. WHY GROSS CROPPED AREA AND PHYSICAL LAND MUST BE SEPARATED

Annual crop activity and physical land are related but not identical. Gross cropped area counts the number of crop cycles or harvested crop areas during a year. Physical land counts the underlying land base. If one physical hectare supports two annual crop cycles, it

contributes two hectares to gross cropped activity but remains one hectare of physical land.

This distinction is especially important when comparing the global model with the India-specific predecessor. The India study reported gross cropped area and then converted it to physical land using a cropping-intensity parameter. The global model retains gross crop activity as the principal functional unit because a global cropping-intensity conversion is less defensible than a direct annual production-area accounting.

The distinction also prevents misleading interpretations of land acquisition. A modelled 600 Mha of additional annual crop activity does not mean that 600 Mha of new land must necessarily be purchased or cleared. Some of that activity could theoretically occur through higher cropping intensity, double cropping, yield improvement or relocation within existing agricultural land.

At the same time, gross cropped area is not a trivial metric. Annual crop activity generates annual requirements for water, fertilizer, labour, seed, machinery and energy. Therefore, even when physical land is unchanged, a large increase in gross crop activity can generate substantial resource demand.

For this reason, the present study reports both annual crop activity and physical-land context where possible. It does not collapse them into a single number.

APPENDIX H. RESOURCE-REQUIREMENT INTERPRETATION

The blue-water, fertilizer and labour modules are deliberately described as screening calculations. Their role is to show the direction and approximate scale of resource requirements generated by the land scenarios, not to substitute for detailed regional models.

Blue-water demand is especially sensitive to geography. A cubic kilometre of irrigation water in a water-abundant basin is not equivalent in scarcity impact to the same volume in an already stressed basin. The present model therefore reports blue-water volume rather than a global scarcity-weighted impact. Future work should combine the crop portfolio with basin-level water-stress characterization.

Fertilizer requirements are expressed as nutrient mass N, P2O5 and K2O rather than commercial fertilizer product mass. This avoids confusion between elemental nutrient quantities and tonnes of urea, DAP or MOP. Organic manure, digestate, biological nitrogen fixation and residue recycling can reduce external fertilizer requirements, but the magnitude of those credits depends on collection, processing, nutrient recovery and substitution assumptions. They are therefore not automatically netted into the direct fertilizer requirement.

Labour is expressed as labour-days rather than employment. This is essential because labour demand is seasonal, spatially distributed and partly supplied by the same workers across several enterprises. A high labour-day requirement does not imply an equivalent number of permanent jobs.

The resource modules therefore function as feasibility indicators. They answer the question: if the crop area required by the nutritional model were actually cultivated under the screening intensities, what additional resource flows would be implied? They do not answer the separate question of whether those resources would be economically or physically available in every location.

APPENDIX I. GHG AND CARBON-DEBT ACCOUNTING RULES

The GHG framework separates annual operational emissions from stock-change carbon debt. For this study, LUC carbon debt is deliberately amortized over a 10-year accounting period, while crop-production emissions recur annually. Treating the stock-change debt and recurring operational emissions as one undifferentiated annual number can obscure the timing of climate effects. The reported LUC Gt CO2e/year values are therefore 10-year-amortized accounting burdens.

The grassland-to-cropland factor of 5.9 t CO2e/ha/year is a screening factor supported by [8], while the forest-to-cropland factor of 7.3 t CO2e/ha/year is from [14]. These source factors have different provenance and should not be treated as directly measured global constants. The present study applies a common 10-year accounting convention: 59 and 73 t CO2e/ha are the corresponding ten-year accounting equivalents, and the reported annual LUC burden is that ten-year carbon debt divided by 10. This is an accounting convention for the study boundary; it does not claim that the carbon is physically emitted at a constant rate for ten years and should not be interpreted as a 100-year amortization.

The livestock phaseout module is also separated. With a 4.3 Gt CO2e/year baseline and a linear ten-year decline, cumulative transition emissions equal 21.5 Gt CO2e. The same quantity represents cumulative avoided emissions relative to an unchanged baseline. It is not appropriate to subtract 21.5 Gt from crop emissions as though the phaseout were an atmospheric removal.

The animal-disposal module is similarly isolated. The 235 Mt CO2e/year value is a hypothetical unmanaged-disposal sensitivity for the existing animal inventory amortized over ten years. It is not a recurring livestock emission. Managed disposal, rendering, composting or other pathways could materially change the outcome.

Finally, manure and biogas are kept as opportunity-cost modules. The same manure cannot simultaneously be credited as fully captured biogas feedstock, fully recovered fertilizer, and fully avoided livestock emissions without an allocation rule. The publication therefore treats these pathways as alternative system benefits rather than automatically additive credits.

APPENDIX J. RECOMMENDED FUTURE RESEARCH PROGRAMME

The next stage of this research should replace global screening assumptions with spatially explicit optimization. First, the harmonized 659.366 Mha primary basis should be re-solved using country- or agro-ecological-zone-specific nutrient targets and crop yields rather than a residual rest-of-world component. Second, the feed-cropland module should be expanded from the defined 100-country analytical set to a complete global inventory with explicit treatment of trade and co-product allocation.

Third, nutrient bioavailability should be upgraded using crop-form-specific human absorption data. Protein quality should distinguish raw, soaked, germinated, fermented and cooked forms where evidence supports such distinctions. Mineral bioavailability should incorporate meal composition rather than applying a single factor to all plant foods.

Fourth, water should be modelled at basin scale with blue-water scarcity characterization. Fertilizer should be linked to soil nutrient balances, biological nitrogen fixation and regional management systems. Labour should be estimated using crop-specific operations and mechanization scenarios.

Fifth, the replacement model should be integrated with an explicit mixed crop-livestock/IFS model. That model could quantify how much food, nutrient, energy and fibre output can be produced per hectare when crop residues, manure, fish ponds, horticulture and livestock are jointly optimized. This would provide a genuine systems comparison rather than inserting IFS as a qualitative argument.

Sixth, future GHG analysis should use spatial land-use-change pathways, explicit carbon pools and time-dependent accounting. The present 10-year LUC amortization is the defined accounting boundary of this study and should be retained when reproducing the reported headline results; future work can additionally test alternative amortization periods and explicit time-dependent carbon-release pathways.

Finally, a future global model should report multiple functional units' side by side: total agricultural land, cropland, physical land, annual cropped activity, digestible protein, bioavailable micronutrients, total food energy and multi-criteria system performance. Doing so would make it possible to compare LCA, LUR, PPA, nutritional-equivalence and integrated-farming results without forcing them into a single headline metric.

APPENDIX K. PUBLICATION AUDIT CHECKLIST

Table 10. Publication audit checklist and interpretation of principal methodological controls.

Audit item	Status	Publication interpretation
Functional unit explicitly stated	Yes	Annual gross crop activity; physical land distinguished.
Nutritional target defined	Yes	Existing ASF nutritional contribution; not RDA adequacy.
Protein quality included	Yes	AA-specific DIAAS-style screening.
Bioavailability included	Yes	Ca, Fe, Zn and vitamin A treated separately.
Calories excluded explicitly	Yes	Boundary choice documented.
PPA rule documented	Yes	Production purpose separated from downstream co-product use.
Feed dataset coverage disclosed	Yes	87 complete; one cereal-only; 12 without usable data in defined set.
Productivity sensitivity disclosed	Yes	90%, 70%, 50% representative cases.

Post-harvest sensitivity disclosed	Yes	13.3% system-level sensitivity.
Water/fertilizer/labour boundary disclosed	Yes	Screening-level modules, not full spatial LCA.
LUC accounting separated	Yes	Operational GHG, carbon debt and phaseout kept distinct.
Phaseout emissions not netted as removals	Yes	Avoided emissions reported separately.
IFS evidence contextualized	Yes	ICAR and 700-study MCLS evidence included with caveats.
Limitations disclosed	Yes	Primary-basis, data coverage, proxies and spatial resolution limitations.
Reproducibility pathway stated	Yes	Workbook, raw inputs, evidence register and change log recommended.

SUPPLEMENTARY RESULTS TABLES FOR PEER REVIEW

A. Table S1. Core land-balance results

Case	Productivity	Replacement area (Mha/y)	Feed credit (Mha/y)	Net additional annual crop-activity equivalent (Mha/y)	% current cropland
A	90%	845.016	215.800	629.216	40.1%
B	70%	1,086.449	167.844	918.605	58.5%
C	50%	1,521.029	119.889	1,401.140	89.2%

B. Table S2. Sensitivity hierarchy

Sensitivity	Base/Case	Output	Interpretation
Primary harmonized basis	659.366 Mha/y	659.366	Working basis
Post-harvest loss	13.3%	760.514 Mha/y	System-level sensitivity
Productivity	90%	629.216 Mha/y net	Higher-productivity case
Productivity	70%	918.605 Mha/y net	Intermediate case
Productivity	50%	1,401.140 Mha/y net	Lower-productivity case
Global cropland context	2023	1,571 Mha	Comparison denominator

C. Table S3. Boundary-control statements

Module	Included	Not automatically included
Nutrition	ASF-derived protein, Ca, Fe, Zn, vitamin A; choline as a boundary target with an incremental screening extension	RDA adequacy, B12, vitamin D, iodine, EPA+DHA
Land	Crop activity, potential feed-land reallocation, productivity sensitivity	Automatic land conversion
Water	Screening blue-water volume	Basin scarcity weighting
Fertilizer	N, P2O5, K2O screening	Automatic manure/fixation credit
GHG	Operational/LUC/phaseout modules	Artificial negative-emission subtraction
IFS	Published system evidence	Automatic global scaling of local results

DETAILED EQUATION COMPENDIUM AND REPRODUCIBILITY PROTOCOL

A. Nutritional replacement equation

For nutrient n, the plant-side production requirement is defined by the target nutritional contribution divided by the usable nutrient contribution of the crop portfolio. In simplified form:

$Q_n = T_n / U_n$

where T_n is the ASF-derived target and U_n is the usable plant-side contribution per unit harvested

production. For protein, U_n is not crude protein concentration alone; it incorporates amino-acid composition and digestibility. For minerals, U_n incorporates the selected nutrient-specific bioavailability factor.
The equation is applied consistently across the system so that the same target is not inadvertently counted more than once.

B. Crop-area equation
For each crop i:
$A_i = P_i / Y_i$
where P_i is the required usable production and Y_i is the applicable yield. Total annual crop activity is:
$A_{total} = \Sigma A_i$
The equation is simple, but the scientific uncertainty is concentrated in P_i and Y_i. P_i depends on nutritional quality and portfolio constraints, while Y_i depends on agroecology, management and productivity scenario.

C. Post-harvest equation
Where L represents the system-level loss fraction:
$Q_{harvest} = Q_{usable} / (1 - L)$
For L = 0.133 and a base annual crop requirement of 659.366 Mha-equivalent activity, the sensitivity produces 760.514 Mha-equivalent activity. This is a sensitivity transformation, not a crop-specific loss observation.

D. Feed-credit equation
The net land requirement is:
$A_{net} = A_{replacement} - A_{feed_credit}$
The feed credit is productivity dependent. It is not a fixed global subtraction. This prevents the model from assuming that all feed-associated land has the same productive potential as the replacement crop portfolio.

E. GCA and physical-land relationship
For systems in which multiple crop cycles are explicitly modelled:
GCA = Physical land × Cropping intensity
and therefore:
Physical land = GCA / Cropping intensity
The present global model does not impose a single global cropping-intensity factor because doing so would conceal major regional differences. The India-specific predecessor uses the relationship explicitly because its national dataset contains a defined cropping-intensity parameter.

F. Ten-year phaseout equation
For a baseline annual livestock emission B and a linear ten-year phaseout:
$E_{transition} = B \times 10 / 2$
For B = 4.3 Gt CO2e/year:
$E_{transition} = 4.3 \times 5 = 21.5$ Gt CO2e
The same 21.5 Gt is the cumulative avoided amount relative to a counterfactual unchanged baseline. The two values are reported separately and are not netted against crop emissions.

G. Reproducibility Protocol
1. Freeze the ASF baseline and record the statistical year for every country/category.
2. Freeze the nutritional target before optimizing the crop portfolio.
3. Record every crop input as observed value, literature parameter, proxy or model output.
4. Apply the same nutrient target to every productivity scenario; only production/yield capacity should change.
5. Recalculate feed credit under each productivity scenario rather than holding it constant.
6. Preserve missing observations as NA and report dataset coverage.
7. Keep annual crop activity, physical land, total agricultural land and land-use-change area as separate variables.
8. Do not combine manure, biogas, fertilizer and GHG credits unless a formal allocation rule is specified.
9. Label all sensitivity outputs as sensitivities rather than replacing the primary estimate.
10. Retain the workbook calculation chain so every headline number can be traced to an input cell, source or equation.

H. Table S4. Reproducibility classification of principal outputs

Output	Type	Primary dependency	Interpretive status
659.366 Mha/y	Harmonized model basis	India anchor + ROW harmonization	Primary working basis

760.514 Mha/y	Sensitivity	13.3% loss	System-level sensitivity
845.016 Mha/y	Scenario output	90% productivity	Representative case
1,086.449 Mha/y	Scenario output	70% productivity	Representative case
1,521.029 Mha/y	Scenario output	50% productivity	Representative case
629.216 Mha/y	Derived net output	90% case − feed credit	Primary high-productivity net case
918.605 Mha/y	Derived net output	70% case − feed credit	Primary intermediate net case
1,401.140 Mha/y	Derived net output	50% case − feed credit	Primary low-productivity net case
239.777 Mha/y	Dataset-derived	Defined feed-country dataset	Conditional feed-land pool